Impacts of Land Use and Land Cover Changes, and Climate Variability on Hydrology and Soil Erosion in the Upper Ruvu Watershed, Tanzania

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Keywords: Land use and land cover change, climate variability, soil erosion, hydrology, SWAT

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Abstract

Land alterations including deforestation, unsustainable land management practices and an increase in cultivated areas have occurred in the Upper Ruvu watershed in recent decades threatening water and natural resources. This study, which used a combination of remote sensing techniques, field experiments, watershed monitoring, and modeling was designed to investigate impacts of environmental changes on hydrology and soil erosion. The objectives were to: map the extent of land use and land cover changes and its influence on soil erosion; correlate the contribution of climate variability and human activities to the changes in hydrology at headwater and watershed scales; estimate surface runoff, sediments and Curve Number at plot scale, and model streamflow responses to changes in land use and land cover using the SWAT watershed model. Results indicate that areas covered by forest decreased from 17% in 1991 to 4% of the total watershed area in 2015. However, areas covered by cropland increased from 14% to 30% of the total watershed area from 1991 to 2015, respectively. Further, results indicate that site characteristics affect runoff and sediment yield as higher soil loss was estimated from cropland with a mean of 28.4 tha^{-1} in 2015 from only 19.8 tha^{-1} in 1991. Results from monitoring show high sediment loads were from the most disturbed watersheds, compared to Mbezi. Analysis of trends for the long term records at the watershed showed that rainfall had significant decreasing trends. At annual scale, climate variability contributed 46% and human activities contributed 54% of the changes in streamflow. Results from the rainfall simulation experiments show upland rice had higher runoff (48 mmh^{-1}) and soil loss (94 gm^{-2}) compared to grassland and forest. Results from the model outputs showed that average streamflow decreased by 13% between 1991 and 2015. Average peak flows increased by 5% and 12% for 2000 and 2015, respectively compared to the baseline. Land alterations had impacts on surface runoff which increased by 75% and baseflow decreased by 66% in 2015 from the baseline. These results highlight the main areas of changes and provide quantitative information for decision makers for sustainable land and water resources and management.

Keywords: Land use and land cover change, climate variability, soil erosion, hydrology, SWAT

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General Audience Abstract

Deforestation, unsustainable land management practices including cultivation in marginal areas, slash and burn, illegal forest harvest; and bush fires have been common threats to the landscapes of the Upper Ruvu watershed in recent decades. These practices have contributed to the deterioration of water and natural resource base and jeopardize sustainability. Our study was designed to investigate the impacts of environmental changes on the hydrology and soil erosion. We used a combination of methods including experiments in the field, remote sensing and mathematical modeling to investigate the extent of the problem and provide useful information for sustainable management of resources. The objectives were to understand the extent and dynamics of land use and land cover change and subsequent influences on soil erosion; to correlate contribution of climate variability and human activities to hydrology at different scales; to estimate surface runoff and sediments at plot scale; and to model and predict streamflow responses to changes in land use and land cover. Our results indicate that the watershed has been characterized by a loss of forest cover which decreased from 17% in 1991 to 4% of the total watershed area in 2015. Areas of the watershed occupied by cropland increased from 14% to 30% of the total watershed area from 1991 to 2015, respectively. Further, results indicate that the changes had effects on runoff and sediment yield as a high increase of soil loss was estimated from cropland which increased from 19.8 t ha^{-1} in 1991 to 28.4 t ha^{-1} in 2015 and areas occupied by forest were least contributors to soil erosion. The assertion is supported by results from a stream-monitoring which revealed that watersheds with least human interferences generated less sediments, and upland rice had higher soil loss compared to grassland and forest. Analysis of rainfall trends showed significant decreasing trends and fluctuations in climate contributed 46%, and human activities contributed 54% of the changes in streamflow signifying impacts on water availability. Results from the model outputs showed that average streamflow decreased by 13% between 1991 and 2015, with increase in peak flows and decrease in baseflow. Results highlight the changes and subsequent consequences on the hydrology of the watershed and water availability. The information is useful for watershed planning and water resources management.

Keywords: Land use and land cover change, climate variability, soil erosion, hydrology, SWAT

Dedication

To my lovely wife Winfrida, my daughter Charity and my son Ethan for the love and inspiration.

To my late mother Elizabeth, I will always cherish and treasure your unconditional love.

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As a child I loved to play and dance in the rain and enjoyed swimming in streams and ponds and always wondered about nature, and was fascinated by rivers and water bodies, little did I know that the quest would take me this far. This journey has been long, but worthy any experience, and would not have come to an end without the help and support rendered to me by many people along the way. The more I think about thanking every individual, the longer the list and the more complicated the task becomes. While I may not be able to list everybody, it is my hope that all the people who in many various ways and capacities have helped me endure the many hurdles along the way, consider my progress as partially theirs. As some people were not occasional partners, they went out of their way to help me succeed and I am indebted to mention them.

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All the Glory and Honor be to God, for without His mercy and care I would be absolutely nobody and nothing.

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List of Abbreviations and Acronyms

DEM	Digital Elevation Model
ENSO	El Nino-Southen Oscillation
ESIA	Environmental and Social Impact Assessment
ET_o	Reference Evapotranspiration
GCPs	Ground Control Points
iAGRI	Innovative Agriculture Research Initiative
ICTZ	Inter-tropical Convergence Transition Zone
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
JICA	JAPAN International Cooperation Agency
LEAP	Leadership Enhancement in Agriculture Program
LULC	Land Use and Land Cover Change
MAM	March to May
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NSE	Nash-Sutcliffe Efficiency
NTU	Nephelometric Turbidity Units
OND	October to December
RSR	Ratio of root mean square to the standard deviation of measured data
RUSLE	Revised Universal Soil Loss Equation
SRTM	Shuttle Radar Topography Mission
SSC	Suspended Sediment Concentration
SSC	Suspended Sediment Concentration
SWAT	Soil and Water Assessment Tool
SWAT-VSA	Soil and Water Assessment Tool – Variable Source Area
TMA	Tanzania Meteorological Agency
USAID	United States Agency for International Development
USDA-ARS	United States Department of Agriculture – Agricultural Research Service
WETSPRO	Water Engineering Time Series PROcessing tool
WHAT	Web GIS-based Hydrograph Analysis Tool
WRWBO	Wami-Ruvu River Water Basin Office

Author’s Preface

This dissertation is comprised of four separate manuscripts (Chapters 2 through 5) preceded by an introductory chapter and followed by the final chapter of major conclusions and highlights areas for future research. The dissertation author is the major contributor and writer of all the four chapters included in this dissertation.

Chapter 1 gives a background information on studies related to the hydrological consequences of land use and land cover change and climate variability around the world, and elucidates on the general problem in the Upper Ruvu Watershed. The author stresses efforts that have been carried out, and the gap that needs to be filled for proper implementation of proper land and water conservation efforts in the watershed.

Chapter 2 explores the changes in the land use and land cover in the Upper Ruvu Watershed for the past 25 years. Using remote sensing and GIS techniques, analysis of Landsat satellite imagery were carried out and major land covers were identified through image classification. Post-classification methods for change detection were used to quantify the change. RUSLE model was used for spatial modeling of soil erosion potential and the change in erosion potential was quantified. The manuscript has been submitted and is under review with the Journal of Land Degradation and Development, 2016.

Chapter 3 presents a discussion about a monitoring program of three headwater watersheds in the upstream of Upper Ruvu Watershed (Mbezi, Mkungazi and Kivumaga), where meteorological and hydrological parameters were monitored for two years. The three watersheds display different levels of degradation due to human activities manifested through the percentage forest cover and percentage of agricultural lands. We found a relationship between levels of degradation and increases in water yield and amount of sediment collected at the outlet of the watersheds. Higher sediment yields were collected from the most degraded watersheds. Overall, the influence of human activities on hydrology were higher compared to climate, which did not differ significantly among the sites. Analysis of long term rainfall, evapotranspiration and discharge data reveal decreasing trends in rainfall in most of the rainfall stations, some which were significant at both annual and seasonal time scales. Changes in quantiles of extreme values displayed decreasing and increasing trends, but most stations showed decreasing trends in precipitation, especially in the recent years. Discharge displayed decreasing trends which were not significant at 0.05 level of significance. Contribution of human activities (such as land clearing, forest conversion, shifting cultivation, grazing and forest encroachment) and climate variability were quantified and indicated that human activities contribute about 54% of changes in streamflow. This manuscript has been submitted to the Journal of Hydrological Processes, 2016.

Chapter 4 presents analysis of runoff and sediment yield experiments using rainfall simulator and estimation of Curve Number at plot scale in the Upper Ruvu watershed. Overall, it was found that agricultural lands generated more amount of runoff and sediments compared to grasslands and forests. Site characteristics, especially ground cover and soil characteristics including initial soil moisture had more influence on the variations in the amount of runoff and sediments generated from the plots. This paper has been submitted and is currently under review with CATENA, 2016.

Chapter 5 evaluates the applicability of two models, SWAT for simulating streamflow responses to changes land use and land cover in a tropical watershed. The model was calibrated and validated using biophysical information collected and analyzed in Chapter 2 through 4, the land use map of 1991, the climate and streamflow data, soil maps, DEM, and land management information. Using the classified land cover maps of 1991, 2000, and 2015 and climate data for 1990 through 2012, the calibrated model was simulated for investigating the changes in streamflow following the changes in land uses. The manuscript has been submitted to the Journal of Water Resources Management.

Chapter 1. Introduction

1.1 Background Information

Water resources around the world are diminishing and water scarcity is already being felt by many people (Jury and Vaux, 2005), and further threatened by deteriorating water quality (Novotny, 2003; Dewan *et al.*, 2012). Water stress is clearly becoming one of the most sensitive issues across the globe (Jenerette and Larsen, 2006; Stehr *et al.*, 2010) and is posing a threat to food production, especially in developing countries where the majority of the population derive their livelihood directly from rainfed agriculture. Water availability and use for such purposes as agriculture, domestic, industries, and environment are becoming unsustainable for climate reasons such as climate variability and climate change as well as non-climatic reasons including increasing demands exacerbated by population growth, urbanization, high levels of consumption and intensified competition for water resources by different sectors. The unprecedented rates of environmental change including changes in land use and land cover (LULC) are likely to cause widespread impacts on hydrology (Eshleman, 2013), land, other economic sectors (Lambin and Meyfroidt, 2011) and on key ecosystem functioning (Lambin *et al.*, 2001). Land use/Land Cover change (LULC) change have become major problems contributing to ecosystems and environmental deterioration of watersheds (Carpenter *et al.*, 1992; Tang *et al.*, 2005; Zhao *et al.*, 2012). Nonetheless, land use and land cover (LULC) is considered to be among the most important components of the terrestrial ecosystems (Lin *et al.*, 2009; Stehr *et al.*, 2010) and are responsible for modifying the bio-geochemical and bio-geophysical cycles, the hydrological cycle including precipitation, evapotranspiration, and land surface temperatures (Feddema *et al.*, 2005; Foley *et al.*, 2005; Stonestrom *et al.*, 2009) and energy exchange of the soil-vegetation-atmosphere system (Breuer *et al.*, 2009), affecting amount of precipitation reaching the ground and consequently increasing runoff during extreme events. Moreover, LULC changes contribute to climate change at local and global scales and remains to be the major cause of land degradation.

Land degradation which refers to a temporary or permanent decline in the productive capacity of the land, or its potential for environmental management is a serious problem in many landscapes around the world, including Sub-Saharan Africa (Lambin *et al.*, 2001). Land degradation has exacerbated watershed degradation through water pollution through sedimentation, eutrophication and impaired recreation, and water shortages for various uses (Richter *et al.*, 2003; Wei *et al.*, 2007; Schilling *et al.*, 2011; Peng and Wang, 2012).The threat of human induced land degradation is also reflected through loss of soil fertility in agricultural lands, and this is directly felt by the majority of smallholder farmers in developing countries like Tanzania. Soil degradation sometimes results into temporary or permanent abandonment of farms and plots and may further result into land conversions to agriculture and grazing. Rapid increases in human population associated with increases in human development activities, that have intensified loss of vegetation cover, and widespread poverty, are among the reasons for increased land degradation in most African landscapes (Sharma *et al.*, 1996).

Soil erosion and associated impacts have increased worldwide mainly due to land use change (Ananda and Herath, 2003; Iqbal *et al.*, 2012), and remain to be major threats to agricultural production. Soil erosion apart from on-site effects such as loss of fertility of the top soil (Gao and Puckett, 2012), is also responsible for the off-site effects such as sedimentation, turbidity in streams and eutrophication in water bodies (Pimentel *et al.*, 1995; Duvert *et al.*, 2010; Fang *et al.*, 2012). Eroded soils are transported from the areas they are generated into stream channels, where some are deposited and can be re-suspended later, while others travel through the stream network of a watershed (Gao and Puckett, 2012). Point sources such as mass movement and non-point sources such as agricultural fields, are responsible for much of the in-stream sediment (De Vente and Poesen, 2005; Gao and Puckett, 2012). It is therefore important to understand the dynamic links between the sources and downstream transport for watershed management (Pimentel *et al.*, 1995). Soil erosion is affected among other things by climate, topography, vegetation and anthropogenic activities.

Growing concerns on the potential consequences of environmental change have attracted research to understand the responses on hydrology and soil erosion and yield valuable information for sustainable agricultural production, and natural resources management. Many studies in several parts of the world have addressed the change in hydrology due to impacts from land uses intensification as a result of increasing human population and changes in climate (Zhang *et al.*, 2008; Li *et al.*, 2009; Lin *et al.*, 2009; Ma *et al.*, 2009; Sterling *et al.*, 2013). Other studies have investigated the impacts of the environmental changes on soil erosion and sediment yield at field, basin and regional scales (Zhang *et al.*, 2008; Mueller *et al.*, 2009; Tang *et al.*, 2011; Defersha and Melesse, 2012; Khoi and Suetsugi, 2014). Numerous studies have stressed the importance of considering scale during the investigation as impacts differ spatially (Wang *et al.*, 2013; Khoi and Suetsugi, 2014). The methods used for assessment in most studies include paired catchments, plot/field scale experiments, statistical analysis (time series) and hydrological modeling (DeFries and Eshleman, 2004; Li *et al.*, 2009; Elliott *et al.*, 2012; Fang *et al.*, 2012; Eshleman, 2013; Khoi and Suetsugi, 2014).

In an attempt to improve the understanding of interrelations between processes involving different environmental factors, plot scale experiments have been widely used (Wendt *et al.*, 1986; Rüttimann *et al.*, 1995; Wainwright *et al.*, 2000) and in recent years these studies have been applied to examine land use and land cover change and their impacts on natural resources (Wainwright *et al.*, 2000; DeFries and Eshleman, 2004; Blackie and Robinson, 2007; Moreira *et al.*, 2011; Eshleman, 2013). Plot-scale studies may be used to elucidate runoff mechanisms, soil erosion and land cover dynamics following these changes. Furthermore, rainfall simulation studies under controlled conditions have been used to study water fluxes, sediment transport processes, (Rüttimann *et al.*, 1995; Wainwright *et al.*, 2000; Moreira *et al.*, 2011; Zhao *et al.*, 2013), and environmental impacts from agricultural activities (Kibet *et al.*, 2014). Although, rainfall simulators were originally used for soil erosion studies (Mutchler and Hermsmeier, 1965), over the decades studies have used rainfall simulators to study not only soil erosion, but also other constituents from surface erosion and soil leachates such as non-point source pollution from agricultural activities (Fu *et al.*, 2011; Elliott *et al.*, 2012; Zhao *et al.*, 2013; Kibet *et al.*, 2014). On the other hand, field and plot studies using natural rainfall (Licznar and Nearing, 2003; Defersha and Melesse, 2012; Peng and Wang, 2012) have been used for assessing environmental change impacts on runoff and soil loss, and trends between the two have been reported to follow a similar pattern indicating consistency in processes (Kibet *et al.*, 2014). Thus, rainfall simulation is being used to predict the likely occurrence of what happens under natural rainfall, mainly because of its easy applicability even in areas where it would otherwise be difficult to conduct research under natural rainfall. Advantages of plot scale experiments include the ability to replicate measurements at both time and space, and the ability to control environmental conditions to some degree. One major disadvantage of the experiments is that they are best suited for measuring processes that are assumed to occur in a vertical dimension and therefore direct extrapolation to larger scales may be misleading.

Small paired/nested catchments experiments offer essential knowledge to elucidate the hydrological and erosive processes under different land uses. These studies have been widely used by different researchers to determine the magnitude of water yield changes resulting from changes in land cover (Brown *et al.*, 2005). Bosch and Hewlett (1982), reviewed watershed experiments to determine the effect of land cover change on water yield. Notable studies have been on the impacts of deforestation, afforestation, and forest conversion on annual water yields, losses due to evapotranspiration, interception rates and floods (DeFries and Eshleman, 2004). Reviews of literature from studies carried over several decades describe the importance of paired watersheds and reveal that much of the current insights into consequences of LULC on hydrology have been elucidated at small, observable scales paired/nested watersheds (Sahin and Hall, 1996; Stednick, 1996; DeFries and Eshleman, 2004; Brown *et al.*, 2005; Eshleman, 2013). Details of small scale experiments and observation date back to early catchment experiments in the early 1900s by Bates (1921) and over the years results have been reported all over the world. Stednick (1996), for example reports that forest reduction of less than 20% magnitude would be difficult to be determined by stream flow measurement methods and therefore discriminating watersheds by region would be essential. Results from other studies have been summarized by other researchers such as Sahin and Hall (1996) and Brown *et al.* (2005). Hornbeck *et al.* (1993), summarized and compared results from 11 catchments in the northeastern USA and found substantial increases in water yield in the first year after forest clearing. Paired watersheds to determine effectiveness of conservation activities and best management practices (BMPs) (Huang *et al.*, 2003; Bishop *et al.*, 2005; Dunkell *et al.*, 2011), assess soil erosion and suspended sediments as a result of land use management and vegetation change (Polyakov *et al.*, 2010; Schilling *et al.*, 2011; Sharma *et al.*, 2011) and to determine effects of fire on runoff, soil, sediment loads and other watershed processes (Ice *et al.*, 2004; Ryan *et al.*, 2011). In Tanzania, first catchment studies were carried under the East African Agricultural and Forestry Research (EAAFRO) with the focus being on the effects of deforestation/afforestation on catchment discharge. Studies by Dagg and Blackie (1965) found small effects of plantation forests and tea on stream flow once plant canopy had completely covered the ground. An increase of almost 50% of stream flow was recorded for a cleared forest compared to a forested (control) watershed (Edwards and Blackie, 1975).

One major benefit of these studies is the availability of good quality experimental data which allows us to understand the hydrologic response of watersheds to land use change and allow testing of mathematical models (DeFries and Eshleman, 2004). However, the limitation associated with small scale experimental data is the lack of experimental replication across a full range of natural conditions (Eshleman, 2013). For example, plantation forests and tea were found to have small effects on stream flow once plant canopy completely covered the ground and had established a deep rooted system (Dagg and Blackie, 1965; and Blackie 1972). In Mbeya, Tanzania where there is a six months dry period, long term average increases in stream flow of about 50% was recorded in a cleared forest compared with the control (forested) (Edwards and Blackie, 1975). Although numerous studies have shown that increase in forest cover can cause a decrease in water discharge due to increased evapotranspiration (Hewlett and Hibbert, 1967; Bosch and Hewlett, 1982), a study in China (Zhang and Lu, 2009) showed results contrary to that. It is well agreed and documented that watershed hydrology is affected by vegetation types, soil properties, geology, terrain, climate, land use practices and management, and spatial patterns of interactions among these factors. There is a general consensus that most of these factors and interactions are influenced by human activities and climate change (Li *et al.*, 2009; Tomer and Schilling, 2009).

While the hydrological effects of complete clearing of forests are adequately established, few basic studies have been done to assess the effects of deforestation on the various components of the hydrologic cycle in Tanzania. Information relating the effects of deforestation on changes in the hydrologic cycle including water quality changes and crop evapotranspiration is scanty. The hydrological effects of land use change have been a cause of controversy and debate for many years, especially the effects of deforestation and afforestation on the dry season flow. Lorup and Hansen (1997) carried out a study in three small headwater catchments in Iringa Region in the southwestern highlands of Tanzania. They compared one year's stream flow response from three catchments with similar physiographic and climatic characteristics. The results revealed that the annual runoff from a catchment with evergreen montane forest was 30 and 36% lower than from two cultivated catchments. The largest difference in runoff was found during the dry season where the total runoff was approximately twice as high from the cultivated catchments.

Statistical analyses in hydrological time series at the usual time scale encountered in water resources studies are based on the following fundamental assumptions; the series is homogenous, stationary, free from trends and shifts and non-periodic with no persistence. The availability of data that have been collected using consistent methods for watersheds is crucial for the time series analysis (DeFries and Eshleman, 2004; Eshleman, 2013). Despite the challenges faced in data collection, data archiving, distribution, and computational capabilities, data for different rivers around the world are now available to allow time series analyses especially in developed countries such as the United States (McCuen, 2003). Eshleman (2013), points that time series methods for identifying and quantifying hydrological responses must be able to distinguish between episodic and circular effects in a long term record (McCuen, 2003). Literature reviews on statistical time series analysis describe that hydrological effects of land use change are complicated by variability caused by long term climate fluctuations and climate change (Li *et al.*, 2009; Eshleman, 2013). It is therefore critical to isolate individual contributions of human activities from those that are caused by climate change. Moreover, statistical analyses require availability of long term data on climatic and hydrologic parameters to allow any useful interpretation. Data collection, archiving and retrieval in developing countries are limited, and therefore long term analyses are problematic.

The use of simulation models has two main aims; to examine the possibility of making certain assumptions about the real world system and to predict the behavior of the real world system under a set of naturally occurring circumstances (Beven, 1989; Beven, 2000; Beven, 2011). Hydrological and erosion models differ in many ways based on process description, temporal and spatial resolution, techniques solution, land use and model use (Singh, 1995). Models can be classified depending upon the way the hydrological processes are described as deterministic, stochastic or mixed and based on process description classified as empirical, lumped, semi-distributed and distributed models (Singh, 1995).

Empirical models at watershed scale have evolved over the years to include rational method, the unity hydrograph, SCS method and the Modified Universal Soil Loss Equation (MUSLE)(Eshleman, 2013) among others. Although tremendous progress has been made in computing and data availability to date, many of the methods are still widely used mostly due to their simplified assumptions (Eshleman, 2013). SCS method for example has been widely used for studies related to impacts of land use change on infiltration in agricultural watersheds as well as for storm runoff in urbanized watersheds. The Curve Number (CN) which is assigned to different hydrologic soil groups and used in SCS and other models (e.g. AGNPS, SWAT) to account for surface runoff was originally developed from experimental watersheds in the USA and take advantage of the wide availability of experimental data. However, the use of the empirical model has a limitation because of the assumptions that the processes occur in a linear way and thus limits the application to small watersheds (Beven, 2000), and are limited to the environment in which they have been developed (Aksoy and Kavvas, 2005).

Process based classification divides models into lumped, semi-distributed and distributed models. While a lumped model uses single values of input parameters with no spatial variability and results in single outputs, distributed models uses spatially distributed parameters and provides spatially distributed outputs taking into account spatial variability of the process (Aksoy and Kavvas, 2005). Physical based simulation models have been supported by the relative advancement of computational capability. Continuous simulation in the physical based models have been important for examining impacts of long term land use and climate change in watersheds. However, lumping or spatial averaging of watershed parameters limits application to small watersheds with homogeneous characteristics (Beven, 1989). Major weaknesses of lumped models include their inability to represent the spatial variability of hydrological process and parameters (Moore *et al.*, 1991), and effective parameters in the model are not directly related to measurable watershed characteristics (Eshleman, 2013).

On the other hand, semi-distributed models permit parameters to vary in space by dividing the basin into a number of smaller sub-basins. Major advantage of these models is that they are physically-based than the structure of lumped models and that they are less data demanding on input data than fully distributed models. Some of the widely used models are shown in Table 1-1.

Table 1- 1. Some hydrological and erosional models

MODEL	EMPIRICAL	CONCEPTUAL	SEMI-DISTRIBUTED	DISTRIBUTED
MIKE-SHE				X
DHSVM				X
TOPLATS				X
WASIM				X
SWAT			X	
TOPMODEL			X	
PRMS			X	
SLURP			X	
HBV			X	
WEPP				X
CASC2D-SED				X
EROSION 3D				X
CREAMS				X
USLE	X			
RUSLE	X			
MUSLE	X			
LASCAM		X		

The use of spatially distributed models has become common in recent years because of their ability to include spatial and temporal variability of both climatic and biophysical parameters. They allow parameters to vary in space at a resolution chosen by the researcher, and incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of the distribution on simulated rainfall-runoff as well as land use change (Beven, 1989).

Soil Water Assessment Tool (SWAT) is one of the models that has been widely used for assessing surface runoff and sediment delivery to reflect impact of changes in land use or land management and climate change in many parts of the world including the data-scarce catchments. In Tanzania SWAT has been used for hydrological modeling of the Kihansi River Catchment (Birhanu, 2009) and Simiyu River Characterization (Mulungu and Munishi, 2007). SWAT has been used for investigating the effects of climate and changing land use in the Ngerengere catchment (Natkhin *et al.*, 2013; Natkhin *et al.*, 2014) and impacts and uncertainties of climate change on hydrology of River Mara Basin (Dessu and Melesse, 2013). The performance of the SWAT model was tested in a data scarce tropical complex catchment in the Pangani River Basin (Ndomba *et al.*, 2008). Apart from the use of the model for runoff prediction, research on the use of the model for non-point pollution modeling including sediments have been conducted in at least two catchments in Tanzania (Ndomba *et al.*, 2005; Ndomba *et al.*, 2008; Kimwaga *et al.*, 2011). SWAT was considered to have performed satisfactorily well in most of the studies, however most of the authors recommended a proper and wider validation efforts in different watersheds before its adoption.

The landscapes of Uluguru Mountains in Morogoro Tanzania are faced with increased human population (URT, 2011) causing rapid land use changes. Unsustainable agricultural practices are widespread in the landscape including shifting cultivation as a result of declining soil fertility (Yanda and Munishi, 2007). The search for new areas for agricultural expansion has resulted into catchment forest encroachment that have led into natural resources depletion and biodiversity loss (Burgess *et al.*, 2002; Yanda and Munishi, 2007; Lopa *et al.*, 2012).

The Uluguru Mountains are recognized for their importance in biodiversity conservation and is a major headwater region for the tributaries of the Ruvu River which supply water to the main city of Dar Es Salaam and other surrounding towns (Bhatia and Buckley, 1998; Burgess *et al.*, 2002; Yanda and Munishi, 2007). The Ruvu River is a major water source for Dare Salaam which has a population of about 4 million people. In addition, the forests provide products including timber, medicinal plants, honey, and eco-tourism, which are important for people living in the vicinity of the forests (Bhatia and Buckley, 1998). High fertile soils and high rainfall almost throughout the year, are major lures for the increase in settlements and agricultural activities along the slopes of the landscape. Escalating population growth in the basin has created demands for more food and more water for domestic uses, industrial, irrigation of crops and horticultural products, and is a main threat to the forests manifesting itself in fragmentation, felling of trees for timber, charcoal, firewood and building pole collection, uncontrolled fires, livestock grazing and clearance for subsistence and cash crop cultivation (Bhatia and Buckley, 1998; Yanda and Munishi, 2007). Moreover, lack of soil conservation techniques to control soil erosion has worsen the situation (Lyamuya, 1994; Ngoye and Machiwa, 2004; IUCN, 2010). Availability of good pasture and water for livestock is an attraction for pastoralists to migrate from other areas into the foothills and lowlands of the Upper Ruvu watershed causing farmers-pastoralists conflicts (IUCN, 2010).

The trend of exploitation and extraction of natural resources is likely to escalate over the coming years and decades, to satisfy the increasing numbers of people in expanding urban areas, putting the sustainability of the watershed resources into serious jeopardy. Alarming rates of soil erosion have been reported in several parts of the Uluguru Mountains (Rapp *et al.*, 1972; Temple, 1972; Yanda and Munishi, 2007; Kimaro *et al.*, 2008; JICA, 2012), subsequently leading to declines in crop productivity (Lopa *et al.*, 2012) and water quality degradation (Ngoye and Machiwa, 2004). The continued extraction of resources in the upstream part of the watershed have caused siltation problems in the rivers and wetlands found in the lower Ruvu plains (Ngoye and Machiwa, 2004), and may further threaten water resources and biodiversity. Suspended sediments and turbidity levels have been increasing in the Mgeta, Ruvu Kibungo tributaries over the last two decades such that turbidity increased from 130 NTU to 185 NTU in only 10 years from 1992 to 2002 (Yanda and Munishi, 2007), and the increasing loads in the river lead to increased water treatment costs downstream (at Ruvu Chini treatment plant) (Yanda and Munishi, 2007; IUCN, 2010; Lopa *et al.*, 2012).

It is estimated that the number of inhabitants in the city of Dar es Salaam alone will reach 6 million by 2020 (IUCN, 2010), an increase that signals shortages of water, such that several alternative sources of water have been identified and examined. One of such alternative is the construction of the Kidunda Dam with an estimated capacity of 190 Mm^3 in the downstream part of the Upper Ruvu watershed to regulate flows in the Ruvu, supply water for Dar es Salaam and other surroundings, provide water for irrigation and water to support livestock, fishing and support ecosystem functioning (IUCN, 2010; ESIA, 2011). On the other hand, the watershed is faced with impacts of climatic variability manifested in the occurrence of hydrological extremes such as droughts that cause decrease of dry season flows and limit the ability to meet the present demand of water requirements (Yanda and Munishi, 2007; IUCN, 2010; ESIA, 2011) and increase in flash floods (IUCN, 2010; ESIA, 2011) which have led to loss of lives, damage to properties and infrastructures. The flash floods in the long rainy season of 2014 is an example of such extreme events that caused havoc in Morogoro and Dar es Salaam (Balile, 2014; TCRS, 2014). In order to sustainably manage water resources for socio-economic and environmental needs in the basin, Tanzania is implementing the Integrated Water Resources Management (IWRM) (WRBWO, 2008), which for the upper Ruvu Watershed and the Ruvu sub-basin is managed by the Wami-Ruvu River Basin Water Office.

Natural resources protection, soil and water conservation measures are needed for the sustainability of the upper Ruvu River watershed. Information on the extent, rate and impacts of land use and land cover changes, trends and variability in climate variables and their subsequent influence on the hydrology and soil erosion in the watershed is important. Unfortunately, this information is difficult to obtain as analyses are hampered by a lack of reliable data and has delayed the design and planning of key interventions for soil and water conservation in the watershed.

1.2 Problem Statement and Rationale

The landscapes of the Uluguru Mountains are home to some of the most diverse species of flora and fauna and are ranked 15th and 6th globally for bird fauna and vertebrates respectively (Bhatia and Buckley, 1998; Burgess *et al.*, 2002; Burgess *et al.*, 2007). According to JICA (2012) report, Upper Ruvu has the highest water potential out of the seven watersheds in the Wami Ruvu Basin with 44% and 37% of annual specific discharge for dry and wet years respectively. In addition, the watershed resources support important economic activities such as agriculture, fishing, mining, industry, eco-tourism and livestock keeping. However, the landscapes in the watershed suffer from land degradation mainly attributed to increased human population that rely on subsistence agriculture, livestock grazing, small scale mining and forest resources for their livelihood (Ngoye and Machiwa, 2004; Mbilinyi *et al.*, 2006; Yanda and Munishi, 2007; Lopa *et al.*, 2012).

Landscapes in the Uluguru Mountains contain about 60% of the population of the Upper Ruvu watershed with an average population density of between 250-300 people/km^2 (URT, 2011). For several decades, the watershed has experienced increased rates of soil erosion and sedimentation problems, and changes in the hydrological regimes (Ngoye and Machiwa, 2004; Yanda and Munishi, 2007; Msaghaa *et al.*, 2014). Land degradation in the watershed has serious economic and environmental consequences affecting not only the human population but also the environment (WRBWO, 2008; IUCN, 2010). A combination of factors including conversion of forests to cultivated lands, inappropriate agricultural practices, logging, bush fires, grazing, climate variations and steep slopes are responsible for the increasing rates (Yanda and Munishi, 2007; IUCN, 2010; JICA, 2012; Msaghaa *et al.*, 2014). Dwindling water supplies downstream, especially in the dry season, flooding in the wet season and deteriorating water quality have been reported (Burgess *et al.*, 2002; Ngoye and Machiwa, 2004; Lopa *et al.*, 2012; Msaghaa *et al.*, 2014) as a result of the environmental changes.

Yanda and Munishi (2007), in a study carried for the entire Ruvu basin, reported a decrease of about 25% and 49% for forests and woodlands respectively in a span of just five years from 1995 to 2000. Increases of about 350% in cultivated land, 31% of grasslands, and about 50% of bushland was reported for the same time from 1995 to 2000. In 1995 cultivated land occupied only 7% of the basin area, but the coverage increased to 32% in 2000 (Yanda and Munishi, 2007). Although this study was conducted for the entire basin, the results highlight the magnitude of change for the upper Ruvu watershed, and the change could be much worse in the resource rich area. The gazetted Uluguru Mountains occupied about 277 km^2 in 1909 (Temple, 1972), but by 2000 only 230 km^2 of the forest were estimated to remain, with a forest of 0.6% per annum between 1977-2000 (Burgess *et al.*, 2002). As of 2002, Burgess *et al.* (2002) reported that evergreen forests were only confined to the catchment forest reserves managed by the government. Most of the catchment forests in the lowlands have since been cleared for agricultural purposes, and the few remaining have shrunk in size and are continually being degraded. The loss of vegetation cover through forest and woodlands encroachment and increase in cultivated lands and grasslands can have devastating impacts on the hydrology and socio-economic activities of a watershed (Bounoua *et al.*, 2002; Foley *et al.*, 2005), accelerating carbon release to the atmosphere from deforestation and burning of vegetation and modification of the climate through mediation of exchanges of energy, momentum and water between the biosphere and atmosphere (Pielke *et al.*; Sellers *et al.*, 1996; Bounoua *et al.*, 2000; Sterling *et al.*, 2013). Alarming rates of soil erosion, a decline of dry season and water quality problems have already been reported (Ngoye and Machiwa, 2004; Yanda and Munishi, 2007).

Despite of its importance of the Upper Ruvu watershed, no studies have focused to understand the extent, dynamics and impacts of environmental changes in the watershed. Studies on the quantification of the impacts of the changes on hydrology and soil erosion are scant because of the lack of information including reliable biophysical data hydro-climatic data. Availability of remote sensing data such as the recent launched Landsat 8 and advances in the algorithms for land use and land cover investigation may present the recent perspective changes in land use and land cover and provide new insights. Yanda and Munishi (2007) attempted to qualitatively analyze the relationship between land degradation and hydrology of the basin, and reported that the upper watersheds (e.g Kibungo, Mgeta, Mvuha, and Mfizigo) contributed approximately 70% of the turbidity in the streams mainly due to their presence in higher slopes. A modeling study using the Water Erosion Prediction Project Model (WEPP) by (Msaghaa *et al.*, 2014) reported that cultivated land in the Mfizigo contributed more than 81% of the soil loss and 86% of sediment yield in the Kibungo watershed.

This study seeks to investigate and quantify impacts of land use/cover and climate variability on hydrology, and soil erosion in the basin, through a combination of field experiments and hydrological modeling. While distributed models are widely used tools for answering the question of how land use and climate variability affect hydrological processes, field experiments are essential for providing site-specific data of variables that influence the processes. The models will be used to simulate streamflow, and soil erosion. The data and models might potentially serve as decision support tools for the key stakeholders in the basin. Understanding how LULCs and climate influence hydrology and sediment yield, will enable planners to formulate policies towards minimizing the undesirable effects of future land use and climate variability on the watershed. The knowledge of the types and consequences of these changes is essential for resource base analysis and development of effective and appropriate response strategies for sustainable management of natural resources. The findings from the study will be important for decision makers, land and water resources planners in formulating and implementing effective and appropriate responses to minimize undesirable effects of land use/cover and climate variability.

1.3 Research Objectives

Studies on the quantification of hydrological and soil erosion responses to vegetation changes have relied on paired catchments or single catchment experiments (Bosch and Hewlett, 1982; Ashton *et al.*, 2005), field observations, statistical approaches (time series analysis) and simulation models (DeFries and Eshleman, 2004; Eshleman, 2013). DeFries and Eshleman (2004) summarized factors hindering the applicability of field and catchment experiments as: cost, short length of hydrological records, natural variability of hydrological systems, difficulties in controlling land use change in real catchments, small number of small-scale experiments and problems of extrapolation and interpolation of the results from small scale to large scale and other catchments. Use of simulation models to provide information that will guide the design of strategies for controlling land degradation and sediment delivery, evaluate yield and sustainability of flows and groundwater for domestic and irrigation is highly needed. Developing countries in the tropics including Tanzania whose economies depend on agriculture are moving towards increasing irrigated areas that will increase food production to ensure food security and meet future food demands. High dependence of the majority of the population on natural resources for livelihood has increased vulnerability of these resources to the changes in population and demands. There is, therefore, a great need for the use of simulation models for quantification of impacts of anthropogenic activities and climate change on the sustainability of natural resources and prediction of the potential responses to the changes. Unfortunately, unavailability of important data for evaluation of the models, has made their application a challenge. Many of the available models have been developed for conditions in the USA or Europe and therefore local empirical data are needed for their adoption.

The overall goal of this research was to investigate the potential consequences of changes in land use and land cover (LULC) and climate variability on the hydrology and soil erosion of a tropical watershed, characterized with complex terrains, variability in climate and increased anthropogenic activities. The study focused on monitoring experiments, field experiments and modeling approach for better understanding of the hydrological processes with the view of providing useful information for improved land and water resources management in the watershed for a sustainable environment. Specific objectives of this study were:

1. Mapping land use and land cover changes and its influence on soil erosion in the Upper Ruvu Watershed
2. Correlate the contribution of climate variability and human activities to the changes in hydrology at headwater and watershed scales.
3. Estimate surface runoff, sediment yield and Curve Number using a rainfall simulator at plot scale

4. Model streamflow responses to changes in land use and land cover in the Upper Ruvu Watershed using the SWAT model.

From these objectives, there are a number of specific questions that provide some focus to this research. The questions following thus help to guide and clarify the focus of this research.

(a) What are the major land cover classes and what is the extent of land use and land cover change (LULC) in the Upper Ruvu watershed for the 1991 to 2015 period?
(b) What are the consequences of changing LULC on soil erosion within the watershed?
(c) What is the contribution of climate variability and human activities in the hydrology of headwater sub-watersheds and at watershed scale?
(d) What are the effects of site characteristis and soil characteristics on runoff volume, rate and sediment yield relationships?
(e) Is the Soil and Water Assessment Tool (SWAT) model suitable for simulating the response of streamflow to the changes in land use and land cover in the watershed?

References

Aksoy H, Kavvas ML. 2005. A review of hillslope and watershed scale erosion and sediment transport models. Catena, **64**: 247-271. DOI: 10.1016/j.catena.2005.08.008.

Ananda J, Herath G. 2003. Soil erosion in developing countries: a socio-economic appraisal. Journal of Environmental Management, **68**: 343-353. DOI: http://dx.doi.org/10.1016/S0301-4797(03)00082-3.

Ashton PJ, Patrick MJ, MacKay HM, Weaver AB. 2005. Integrating biodiversity concepts with good governance to support water resources management in South Africa. Water Sa, **31**: 449-456.

Balile D. 2014. Flooding causes severe damage, claims 15 lives in Tanzania. SABAHI Online.

Bates CG. 1921. First results in the streamflow experiment, Wagon Wheel Gap, Colorado. Journal of Forestry, **19**: 402-408.

Beven K. 1989. Changing ideas in hydrology — The case of physically-based models. Journal of Hydrology, **105**: 157-172. DOI: http://dx.doi.org/10.1016/0022-1694(89)90101-7.

Beven K. 2000. Rainfall–Runoff Modelling: The Primer. John Wiley & Sons, Ltd, pp: 51-82.

Beven KJ. 2011. Rainfall-Runoff Modelling : The Primer. Wiley-Blackwell.

Bhatia Z, Buckley P. 1998. The Uluguru slopes planning project: promoting community involvement in biodiversity conservation. Journal of East African Natural History, **87**: 339-347.

Birhanu BZ. 2009. Hydrological modeling of the Kihansi river catchment in South Central Tanzania using SWAT model. International Journal of Water Resources and Environmental Engineering, **1**: 001-010.

Bishop PL, Hively WD, Stedinger JR, Rafferty MR, Lojpersberger JL, Bloomfield JA. 2005. Multivariate analysis of paired watershed data to evaluate agricultural best management practice effects on stream water phosphorus. Journal of environmental quality, **34**: 1087-1101. DOI: 10.2134/jeq2004.0194.

Blackie JR, Robinson M. 2007. Development of catchment research, with particular attention to Plynlimon and its forerunner, the East African catchments. Hydrol. Earth Syst. Sci., **11**: 26-43. DOI: 10.5194/hess-11-26-2007.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, **55**: 3-23. DOI: http://dx.doi.org/10.1016/0022-1694(82)90117-2.

Bounoua L, Collatz GJ, Los SO, Sellers PJ, Dazlich DA, Tucker CJ, Randall DA. 2000. Sensitivity of Climate to Changes in NDVI. Journal of Climate, **13**: 2277-2292. DOI: 10.1175/1520-0442(2000)013<2277:SOCTCI>2.0.CO;2.

Bounoua L, DeFries R, Collatz GJ, Sellers P, Khan H. 2002. Effects of Land Cover Conversion on Surface Climate. Climatic Change, **52**: 29-64. DOI: 10.1023/A:1013051420309.

Breuer L, Huisman JA, Willems P, Bormann H, Bronstert A, Croke BFW, Frede HG, Gräff T, Hubrechts L, Jakeman AJ, Kite G, Lanini J, Leavesley G, Lettenmaier DP, Lindström G, Seibert J, Sivapalan M, Viney NR. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. Advances in Water Resources, **32**: 129-146. DOI: http://dx.doi.org/10.1016/j.advwatres.2008.10.003.

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology, **310**: 28-61. DOI: http://dx.doi.org/10.1016/j.jhydrol.2004.12.010.

Burgess N, Butynski T, Cordeiro N, Doggart N, Fjeldså J, Howell K, Kilahama F, Loader S, Lovett J, Mbilinyi B. 2007. The biological importance of the Eastern Arc Mountains of Tanzania and Kenya. Biological conservation, **134**: 209-231.

Burgess N, Doggart N, Lovett JC. 2002. The Uluguru Mountains of eastern Tanzania: the effect of forest loss on biodiversity. Oryx, **36**: 140-152.

Carpenter SR, Fisher SG, Grimm NB, Kitchell JF. 1992. Global change and freshwater ecosystems. Annual Review of Ecology and Systematics: 119-139.

Dagg M, Blackie JR. 1965. STUDIES OF THE EFFECTS OF CHANGES IN LAND USE ON THE HYDROLOGICAL CYCLE IN EAST AFRICA BY MEANS OF EXPERIMENTAL CATCHMENT AREAS. International Association of Scientific Hydrology. Bulletin, **10**: 63-75. DOI: 10.1080/02626666509493424.

De Vente J, Poesen J. 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth-Sci Rev, **71**: 95-125.

Defersha MB, Melesse AM. 2012. Field-scale investigation of the effect of land use on sediment yield and runoff using runoff plot data and models in the Mara River basin, Kenya. CATENA, **89**: 54-64. DOI: http://dx.doi.org/10.1016/j.catena.2011.07.010.

DeFries R, Eshleman KN. 2004. Land-use change and hydrologic processes: a major focus for the future. Hydrological Processes, **18**: 2183-2186. DOI: 10.1002/hyp.5584.

Dessu SB, Melesse AM. 2013. Impact and uncertainties of climate change on the hydrology of the Mara River basin, Kenya/Tanzania. Hydrological Processes, **27**: 2973-2986.

Dewan AM, Yamaguchi Y, Ziaur Rahman M. 2012. Dynamics of land use/cover changes and the analysis of landscape fragmentation in Dhaka Metropolitan, Bangladesh. GeoJournal, **77**: 315-330. DOI: 10.1007/s10708-010-9399-x.

Dunkell DO, Bruland GL, Evensen CI, Litton CM. 2011. Runoff, Sediment Transport, and Effects of Feral Pig (Sus scrofa) Exclusion in a Forested Hawaiian Watershed. PACIFIC SCIENCE, **65**: 175-194. DOI: 10.2984/65.2.175.

Duvert C, Gratiot N, Evrard O, Navratil O, Némery J, Prat C, Esteves M. 2010. Drivers of erosion and suspended sediment transport in three headwater catchments of the Mexican Central Highlands. Geomorphology, **123**: 243-256. DOI: 10.1016/j.geomorph.2010.07.016.

Elliott AH, Oehler F, Schmidt J, Ekanayake JC. 2012. Sediment modelling with fine temporal and spatial resolution for a hilly catchment. Hydrological Processes, **26**: 3645-3660. DOI: 10.1002/hyp.8445.

Eshleman KN. 2013. Hydrological Consequences of Land Use Change: A Review of the State-of-Science. In: Ecosystems and Land Use Change, American Geophysical Union, pp: 13-29.

ESIA. 2011. Environmental and Social Impact Assessment Report for KIDUNDA DAM. pp: 437 pp.

Fang N-F, Shi Z-H, Li L, Guo Z-L, Liu Q-J, Ai L. 2012. The effects of rainfall regimes and land use changes on runoff and soil loss in a small mountainous watershed. CATENA, **99**: 1-8. DOI: http://dx.doi.org/10.1016/j.catena.2012.07.004.

Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM. 2005. The importance of land-cover change in simulating future climates. Science, **310**: 1674-1678.

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK. 2005. Global Consequences of Land Use. Science, **309**: 570-574. DOI: 10.1126/science.1111772.

Fu Z, Li Z, Cai C, Shi Z, Xu Q, Wang X. 2011. Soil thickness effect on hydrological and erosion characteristics under sloping lands: A hydropedological perspective. Geoderma, **167–168**: 41-53. DOI: http://dx.doi.org/10.1016/j.geoderma.2011.08.013.

Gao P, Puckett J. 2012. A new approach for linking event-based upland sediment sources to downstream suspended sediment transport. Earth Surface Processes and Landforms, **37**: 169-179. DOI: 10.1002/esp.2229.

Hewlett JD, Hibbert AR. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In: Forest Hydrology., In: Sopper WE, Lull, H.W. (Eds.), (ed.) Pegamon, pp: 275-290.

Hornbeck JW, Adams MB, Corbett ES, Verry ES, Lynch JA. 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology, **150**: 323-344. DOI: http://dx.doi.org/10.1016/0022-1694(93)90115-P.

Huang M, Gallichand J, Zhang P. 2003. RUNOFF AND SEDIMENT RESPONSES TO CONSERVATION PRACTICES: LOESS PLATEAU OF CHINA. JAWRA Journal of the American Water Resources Association, **39**: 1197-1207. DOI: 10.1111/j.1752-1688.2003.tb03702.x.

Ice GG, Neary DG, Adams PW. 2004. Effects of wildfire on soils and watershed processes. JOURNAL OF FORESTRY, **102**: 16-20.

Iqbal MN, Oweis TY, Ashraf M, Hussain B, Majid A. 2012. Impact of Land-Use Practices on Sediment Yield in the Dhrabi Watershed of Pakistan. Journal of Environmental Science and Engineering, **1**: 406-420.

IUCN. 2010. IUCN Eastern and Southern Africa Programme, 2010. The Ruvu Basin: A Situation Analysis., xvi + 96 pp. IUCN - ESARO Publications Service Unit

IUCN. 2010. Ruvu Basin: A Situational Analysis. Ngana J, Mahay F, Cross C (eds.) International Union for Conservation of Nature and Natural Resources.

Jenerette GD, Larsen L. 2006. A global perspective on changing sustainable urban water supplies. Global and Planetary Change, **50**: 202-211.

JICA. 2012. The Study on Water Resources Management and Development in Wami/Ruvu Basin in the United Republic of Tanzania. Ministry of Water (MoW).

Jury WA, Vaux H. 2005. The role of science in solving the world's emerging water problems. Proceedings of the National Academy of Sciences of the United States of America, **102**: 15715-15720. DOI: 10.1073/pnas.0506467102.

Khoi DN, Suetsugi T. 2014. The responses of hydrological processes and sediment yield to land-use and climate change in the Be River Catchment, Vietnam. Hydrological Processes, **28**: 640-652. DOI: 10.1002/hyp.9620.

Kibet LC, Saporito LS, Allen AL, May EB, Kleinman PJA, Hashem FM, Bryant RB. 2014. A Protocol for Conducting Rainfall Simulation to Study Soil Runoff. e51664. DOI: doi:10.3791/51664.

Kimaro DN, Poesen J, Msanya BM, Deckers JA. 2008. Magnitude of soil erosion on the northern slope of the Uluguru Mountains, Tanzania: Interrill and rill erosion. CATENA, **75**: 38-44. DOI: http://dx.doi.org/10.1016/j.catena.2008.04.007.

Kimwaga R, Mashauri D, Bukirwa F, Banadda N, Wali U, Nhapi I, Nansubuga I. 2011. Modelling of non-point source pollution around lake victoria using swat model: a case of simiyu catchment tanzania. Open Environ. Eng. J, **4**: 112-123.

Lambin EF, Meyfroidt P. 2011. Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences, **108**: 3465-3472. DOI: 10.1073/pnas.1100480108.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skånes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J. 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change, **11**: 261-269. DOI: http://dx.doi.org/10.1016/S0959-3780(01)00007-3.

Li Z, Liu W-z, Zhang X-c, Zheng F-l. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. Journal of Hydrology, **377**: 35-42. DOI: http://dx.doi.org/10.1016/j.jhydrol.2009.08.007.

Licznar P, Nearing MA. 2003. Artificial neural networks of soil erosion and runoff prediction at the plot scale. CATENA, **51**: 89-114. DOI: http://dx.doi.org/10.1016/S0341-8162(02)00147-9.

Lin W, Zhang L, Du D, Yang L, Lin H, Zhang Y, Li J. 2009. Quantification of land use/land cover changes in Pearl River Delta and its impact on regional climate in summer using numerical modeling. Regional Environmental Change, **9**: 75-82. DOI: 10.1007/s10113-008-0057-5.

Lopa D, Mwanyoka I, Jambiya G, Massoud T, Harrison P, Ellis-Jones M, Blomley T, Leimona B, van Noordwijk M, Burgess ND. 2012. Towards operational payments for water ecosystem services in Tanzania: a case study from the Uluguru Mountains. Oryx, **46**: 34-44. DOI: doi:10.1017/S0030605311001335.

Lyamuya V. 1994. Socio-economic and land use factors affecting the degradation of the Uluguru Mountains catchment in Morogoro Region, Tanzania. BirdLife International.

Ma X, Xu J, Luo Y, Prasad Aggarwal S, Li J. 2009. Response of hydrological processes to land-cover and climate changes in Kejie watershed, south-west China. Hydrological Processes, **23**: 1179-1191. DOI: 10.1002/hyp.7233.

Mbilinyi B, Malimbwi R, Shemwetta D, Songorwa A, Zahabu E, Katani J, Kashaigili J. 2006. Forest area baseline for the Eastern Arc Mountains. Dar es Salaam: Forestry and Beekeeping Division, Ministry of Natural Resources and Tourism.

McCuen RH. 2003. Modeling hydrologic change : statistical methods. Lewis Publishers.

Moore ID, Grayson RB, Ladson AR. 1991. Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrological Processes, **5**: 3-30. DOI: 10.1002/hyp.3360050103.

Moreira LFF, de Oliveira Silva F, Chen S, de Almeida Andrade HT, da Silva JHT, Righetto AM. 2011. Plot-scale experimental studies. Soil Erosion Studies, **7**: 151-166.

Msaghaa JJ, Melesse AM, Ndomba PM. 2014. Modeling Sediment Dynamics: Effect of Land Use, Topography, and Land Management in the Wami-Ruvu Basin, Tanzania. In: Nile River Basin, Springer, pp: 165-192.

Mueller EN, Francke T, Batalla RJ, Bronstert A. 2009. Modelling the effects of land-use change on runoff and sediment yield for a meso-scale catchment in the Southern Pyrenees. Catena, **79**: 288-296. DOI: 10.1016/j.catena.2009.06.007.

Mulungu DM, Munishi SE. 2007. Simiyu River catchment parameterization using SWAT model. Physics and Chemistry of the Earth, Parts A/B/C, **32**: 1032-1039.

Mutchler CK, Hermsmeier. 1965. A Review of Rainfall Simulators. Transactions of the ASAE, **8**: 67-68. DOI: doi: 10.13031/2013.40428 (1965).

Natkhin M, Dannowski R, Dietrich O, Steidl J, Lischeid G. 2014. Model-Based Impact Analysis of Climate and Land Use Changes on the Landscape Water Balance. In: Novel Measurement and Assessment Tools for Monitoring and Management of Land and Water Resources in Agricultural Landscapes of Central Asia, Mueller L, Saparov A, Lischeid G (eds.) Springer International Publishing, pp: 577-590.

Natkhin M, Dietrich O, Schäfer M, Lischeid G. 2013. The effects of climate and changing land use on the discharge regime of a small catchment in Tanzania. Regional Environmental Change: 1-12. DOI: 10.1007/s10113-013-0462-2.

Ndomba P, Mtalo F, Killingtveit A. 2005. The suitability of SWAT model in sediment yield modelling for ungauged catchments. A case of Simiyu subcatchment, Tanzania. In: Proc. 3rd Int. SWAT conf, pp: 61-69.

Ndomba P, Mtalo F, Killingtveit A. 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. Physics and Chemistry of the Earth, Parts A/B/C, **33**: 626-632.

Ndomba PM, Mtalo FW, Killingtveit Å. 2008. A guided SWAT model application on sediment yield modeling in Pangani River basin: Lessons learnt. Journal of Urban and Environmental Engineering, **2**: 53-62.

Ngoye E, Machiwa JF. 2004. The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Physics and Chemistry of the Earth, Parts A/B/C, **29**: 1161-1166. DOI: http://dx.doi.org/10.1016/j.pce.2004.09.002.

Novotny V. 2003. Water quality: Diffuse pollution and watershed management. 2 Edn., J. Wiley & Sons.

Peng T, Wang S-j. 2012. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. CATENA, **90**: 53-62. DOI: http://dx.doi.org/10.1016/j.catena.2011.11.001.

Pielke RA, Avissar R, Raupach M, Dolman AJ, Zeng XB, Denning AS. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. Glob Change Biol, **4**: 461-475. DOI: citeulike-article-id:2929951.

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R. 1995. Environmental and Economic Costs of Soil Erosion and Conservation Benefits. Science, **267**: 1117-1123. DOI: 10.1126/science.267.5201.1117.

Polyakov VO, Nearing MA, Nichols MH, Scott RL, Stone JJ, McClaran MP. 2010. Long-term runoff and sediment yields from small semiarid watersheds in southern Arizona. WATER RESOURCES RESEARCH, **46**. DOI: 10.1029/2009WR009001.

Rapp A, Berry L, Temple P. 1972. Studies of soil erosion and sedimentation in Tanzania. Bureau of Resource Assessment and Land Use Planning, University of Dar es Salaam.

Richter BD, Mathews R, Harrison DL, Wigington R. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. Ecological Applications, **13**: 206-224.

Rüttimann M, Schaub D, Prasuhn V, Rüegg W. 1995. Measurement of runoff and soil erosion on regularly cultivated fields in Switzerland — some critical considerations. CATENA, **25**: 127-139. DOI: http://dx.doi.org/10.1016/0341-8162(95)00005-D.

Ryan SE, Dwire KA, Dixon MK. 2011. Impacts of wildfire on runoff and sediment loads at Little Granite Creek, western Wyoming. Geomorphology, **129**: 113-130. DOI: 10.1016/j.geomorph.2011.01.017.

Sahin V, Hall MJ. 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology, **178**: 293-309. DOI: http://dx.doi.org/10.1016/0022-1694(95)02825-0.

Schilling KE, Isenhart TM, Palmer JA, Wolter CF, Spooner J. 2011. Impacts of Land-Cover Change on Suspended Sediment Transport in Two Agricultural Watersheds. JAWRA Journal of the American Water Resources Association, **47**: 672-686. DOI: 10.1111/j.1752-1688.2011.00533.x.

Sellers PJ, Bounoua L, Collatz GJ, Randall DA, Dazlich DA, Los SO, Berry JA, Fung I, Tucker CJ, Field CB, Jensen TG. 1996. Comparison of Radiative and Physiological Effects of Doubled Atmospheric CO2 on Climate. Science, **271**: 1402-1406. DOI: 10.1126/science.271.5254.1402.

Sharma A, Tiwari KN, Bhadoria PBS. 2011. Effect of land use land cover change on soil erosion potential in an agricultural watershed. Environmental monitoring and assessment, **173**: 789-801. DOI: 10.1007/s10661-010-1423-6.

Sharma NP, Damhaug T, Gilgan-Hunt E, Grey D, Okaru V, Rothberg D. 1996. African Water Resources; Challenges and Opportunities for Sustainable Development (No. 331).

Singh VP. 1995. Computer models of watershed hydrology. Rev. Edn., Water Resources Publications, xiv, 1130 p. Highlands, Colo.

Stednick JD. 1996. Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology, **176**: 79-95. DOI: http://dx.doi.org/10.1016/0022-1694(95)02780-7.

Stehr A, Aguayo M, Link O, Parra O, Romero F, Alcayaga H. 2010. Modelling the hydrologic response of a mesoscale Andean watershed to changes in land use patterns for environmental planning. Hydrology and Earth System Sciences, **14**: 1963-1977.

Sterling SM, Ducharne A, Polcher J. 2013. The impact of global land-cover change on the terrestrial water cycle. **3**.

Stonestrom DA, Scanlon BR, Zhang L. 2009. Introduction to special section on Impacts of Land Use Change on Water Resources. Water Resources Research, **45 (7)**. DOI: Artn W00a00 Doi 10.1029/2009wr007937.

Tang L, Yang D, Hu H, Gao B. 2011. Detecting the effect of land-use change on streamflow, sediment and nutrient losses by distributed hydrological simulation. Journal of Hydrology, **409**: 172-182.

Tang Z, Engel B, Pijanowski B, Lim K. 2005. Forecasting land use change and its environmental impact at a watershed scale. Journal of environmental management, **76**: 35-45.

TCRS. 2014. Latest info on flooding in Dar Es Salaam. Kanyambo R (ed.).

Temple PH. 1972. Soil and Water Conservation Policies in the Uluguru Mountains, Tanzania. Geografiska Annaler. Series A, Physical Geography, **54**: 110-123. DOI: 10.2307/520762.

Tomer MD, Schilling KE. 2009. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. Journal of Hydrology, **376**: 24-33. DOI: http://dx.doi.org/10.1016/j.jhydrol.2009.07.029.

URT. 2011. United Republic of Tanzania (2011). Morogoro District Profile, Prime Minister's Office: Ministry of Regional Administration and Local Government, Morogoro, Tanzania.

Wainwright J, Parsons AJ, Abrahams AD. 2000. Plot-scale studies of vegetation, overland flow and erosion interactions: case studies from Arizona and New Mexico. Hydrological Processes, **14**: 2921-2943. DOI: 10.1002/1099-1085(200011/12)14:16/17<2921::AID-HYP127>3.0.CO;2-7.

Wang W, Shao Q, Yang T, Peng S, Xing W, Sun F, Luo Y. 2013. Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. Hydrological Processes, **27**: 1158-1174. DOI: 10.1002/hyp.9299.

Wei W, Chen L, Fu B, Huang Z, Wu D, Gui L. 2007. The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China. Journal of Hydrology, **335**: 247-258. DOI: http://dx.doi.org/10.1016/j.jhydrol.2006.11.016.

Wendt RC, Alberts EE, Hjelmfelt AT. 1986. Variability of Runoff and Soil Loss from Fallow Experimental Plots1. Soil Sci. Soc. Am. J., **50**: 730-736. DOI: 10.2136/sssaj1986.03615995005000030035x.

WRBWO. 2008. Wami /Ruvu Basin Water Office (WRBWO). 2008. Business Plan.

Yanda P, Munishi P. 2007. Hydrologic and Land Use/Cover Change Analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) Watersheds. For WWF/CARE Dar es Salaam, Tanzania.

Zhang S, Lu XX. 2009. Hydrological responses to precipitation variation and diverse human activities in a mountainous tributary of the lower Xijiang, China. CATENA, **77**: 130-142. DOI: http://dx.doi.org/10.1016/j.catena.2008.09.001.

Zhang X, Yu X, Wu S, Cao W. 2008. Effects of changes in land use and land cover on sediment discharge of runoff in a typical watershed in the hill and gully loess region of northwest China. Frontiers of Forestry in China, **3**: 334-341. DOI: 10.1007/s11461-008-0056-1.

Zhang X, Zhang L, Zhao J, Rustomji P, Hairsine P. 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. Water Resources Research, **44**: W00A07. DOI: 10.1029/2007WR006711.

Zhao XI, Wua P, Chen XL, Helmers MJ, Zhou XB. 2013. Runoff and sediment yield under simulated rainfall on hillslopes in the Loess Plateau of China. SOIL RESEARCH, **51**: 50-58. DOI: 10.1071/SR12239.

Zhao Y, Zhang K, Fu Y, Zhang H. 2012. Examining Land-Use/Land-Cover Change in the Lake Dianchi Watershed of the Yunnan-Guizhou Plateau of Southwest China with Remote Sensing and GIS Techniques: 1974–2008. International journal of environmental research and public health, **9**: 3843-3865.

Chapter 2. Mapping Land Use and Land Cover Changes and its influence on Soil Erosion in the Upper Ruvu Watershed, Tanzania

Abstract

Soil erosion by water is a pressing environmental problem affecting the sustainability of many landscapes in Tanzania. Landscapes in the Uluguru Mountains in Tanzania are affected by an increase of population leading to forest conversions into cropland and grazing areas. Land use/land cover (LULC) change and its impacts on soil erosion were investigated in the Upper Ruvu Watershed over a 25 year period (1991 through 2015) using Landsat imagery and remote sensing techniques. Eight land use/land cover classes were identified and generated at three different time periods (1991, 2000, and 2015). LULC classification was done using Random Forests (RFs) algorithm and satisfactory classification accuracy with kappa coefficients of 92%, 89% and 92% were obtained for the 1991, 2000 and 2015 data respectively. Results show a decrease of natural forests by 77%, woodlands by 44% and wetland by 50%, and an increase of croplands by 111%, shrubland by 39% and grasslands between 1991 and 2015. The Revised Universal Soil Loss Equation (RUSLE) model was used to estimate the influence of the changing land uses on soil erosion. Mean soil losses of up to 34 t/ha/year were estimated in the uplands compared to mean soils of 2 t/ha/year in the lowlands. Higher soil erosion was estimated in the uplands which are characterized by steep slopes and higher rainfall, compared to the lowlands and foothills. Higher soil losses were estimated in cropland with a mean average of 28.4 t/ha/year in 2015 from just 19.8 t/ha/year in 1991 and negligible in natural forests. Average annual soil losses for the entire watershed were estimated to be 5.4, 7.5 and 14 t/ha/year for 1991, 2000 and 2015 respectively, showing increasing soil erosion with continued land use change. About 13% of the watershed was estimated to be in the high to severe erosion risk. Soil erosion rates were higher in sub-watersheds located in the uplands with soils losses ranging from 26 to 47 t/ha/year. These results help to quantify the extent and impact of soil erosion in the watershed, and identify areas contributing to sedimentation in the river and those areas at greater risk for land degradation.

Key words: Land use, Land cover change, remote sensing, soil erosion potential, RUSLE, Landsat

2.1 Introduction

Soil erosion is a major concern for human sustainability (Lal, 1998) in many parts of Tanzania, especially on the steep slopes of mountainous areas like the Uluguru Mountains whose landscapes are highly populated and converted into farmlands. On-site consequences of soil erosion include loss of soil fertility due to the decline in inorganic matter and nutrients (Biro *et al.*, 2013; Leh *et al.*, 2013; Gao *et al.*, 2014; Muñoz-Rojas *et al.*, 2015) can be devastating for crop productivity (Bewket and Teferi, 2009; Morgan, 2009; Ochoa-Cueva *et al.*, 2015). On the other hand off-site impacts such as increase in turbidity, sedimentation, eutrophication and siltation affect water quality and reduce capacity of rivers, reservoirs and dams downstream. Changes in land use and land cover (LULC) as a result of increasing human population and subsequent responses to changing economic activities have affected the environment in pervasive ways (Lambin *et al.*, 2001; Foley *et al.*, 2005). Apart from soil erosion changes in LULC contribute to watershed destruction leading to water pollution and water shortage, habitat destruction (Lambin *et al.*, 2003), biodiversity loss and species extinction (Richter *et al.*, 2003; Vanacker *et al.*, 2007; Wei *et al.*, 2007; Schilling *et al.*, 2011; Peng and Wang, 2012).

The Uluguru Mountains are recognized as an area of global importance for biodiversity conservation (Burgess *et al.*, 2002; Burgess *et al.*, 2007), and important sources of water supply to the Ruvu River. The Ruvu River is a principal water supply to Dar Es Salaam City serving a population of about 5 million people, and other surrounding towns (Burgess *et al.*, 2002). The Upper Ruvu watershed is part of the Ruvu River Basin which join the Wami to form the Wami Ruvu Basin (WRBWO, 2008). According to a JICA (2012) report, Upper Ruvu has the highest water potential out of the seven watersheds in the Wami Ruvu Basin with 44% and 37% of annual specific discharge for dry and wet years, respectively. However, the landscapes in the watershed suffer from deforestation that is mainly attributed to increased human population (Yanda and Munishi, 2007) and is susceptible to soil erosion (Rapp *et al.*, 1972; Kimaro *et al.*, 2008; Mulengera *et al.*, 2010), affecting not only human population, but also ecosystems(Burgess *et al.*, 2002; Yanda and Munishi, 2007). Dwindling water supplies downstream, especially in the dry season, flooding in the wet season and deteriorating water quality have been reported (Burgess *et al.*, 2002; Ngoye and Machiwa, 2004; Lopa *et al.*, 2012; Msaghaa *et al.*, 2014).

The uplands of the Upper Ruvu accommodate approximately 60% of the population in the landscape (NBS, 2012). The majority of the population depend on subsistence agriculture and directly derive their livelihood from natural resources (Ngoye and Machiwa, 2004; Mbilinyi *et al.*, 2006; Yanda and Munishi, 2007; Lopa *et al.*, 2012). Yanda and Munishi (2007) in a study conducted in the entire Ruvu River Basin, reported a change of cultivated land from 7% of total area in 1995 to 32% of total area in 2000, and decrease of natural forests from 8% of the total area to 6% of total area in the same time. A decrease in woodlands and increase in grasslands were also reported, thus increasing the exposure of land surface to erosion and increased surface runoff. Earlier studies in Mgeta and other areas (Temple, 1972; Temple and Murray-Rust, 1972; Temple and Rapp, 1972) (Lundgren, 1978) suggest that soil erosion problems has been known before the 1970s. Several conservation measures had been introduced during the German-British colonial rules, but all failed as they were unsoundly based and ill-advisedly implemented (Temple, 1972; Lundgren, 1978).

Furthermore, it is estimated that the number of inhabitants in the city of Dar Es Salaaam alone will reach 6 million by 2020 (IUCN, 2010). The city will likely face water shortages as a result of the population increase considering current water infrastructures. The construction of the Kidunda Dam on the downstream part of the Upper Ruvu watershed has been identified as one of the solutions to deal with water shortages, regulate flows in the Ruvu River and provide water for other socio-economic activities and ecosystem functioning (ESIA, 2011; IUCN, 2010). However, changes in LULC especially deforestation are likely to result in sediments and siltation in the dam and other downstream areas. Sediments from eroded soils in the uplands have been reported to affect downstream areas including wetlands (Ngoye and Machiwa, 2004) and have resulted in rising water treatment costs (Lopa *et al.*, 2012). Unfortunately, the extent of land cover change and its influence on soil erosion are still not well understood mainly because of lack of adequate temporal and spatial information on LULC change. Understanding the influence of changes in LULC is essential for proper planning of strategies to combat soil erosion and improve watershed management. Availability of the information would enable planning and development of proper soil and land management plans and strategies, enable focus on priority watersheds that would provide best return on investments in the Upper Ruvu Watershed and in other similar areas of Tanzania and Sub-Saharan Africa, as well as setting of priorities and education to create awareness on soil and water conservation projects. This is particularly important as efforts to convince major water users (buyers) downstream to pay for watershed services and address poverty of the poor upstream farmers in a win-win situation.

Land use and land cover mapping using remotely sensed data not only provides a current inventory of resources and land-use, but also offers an opportunity to identify and monitor changing patterns of LULC (Peterson *et al.*, 2004). Remote sensing and geographic information systems have become indispensable tools for monitoring and analysis of LULC for developing countries like Tanzania. As soil erosion is highly associated with changes in land use/cover, characterization and detection of changes allows resource and decision makers to monitor landscape dynamics over large stretch of areas even in the most challenging and difficult terrains. The Revised Soil Loss Equation (RUSLE) (Renard *et al.*, 1997) is used to estimate annual soil loss data in most parts of the world (Mutua *et al.*, 2006; Ochoa-Cueva *et al.*, 2015), largely because of its less requirement of data inherent with most developing countries. Availability of the spatial information on land use and land cover change and knowledge on soil erosion are crucial for sustainable management of the Upper Ruvu watershed.

The objective of the study was to investigate the changes in land use and land cover from 1991 to 2015 in the Upper Ruvu Watershed and quantify the impacts on soil erosion. Specifically, this study was designed to answer the following questions: (a) What are the spatial trends in LULC conversion for the past 25 years change, and (b) what are the consequences of this change in LULC on soil erosion within the watershed?

2.2 Materials and Methods

2.2.1 Study Area

The Upper Ruvu watershed is located within Eastern Arc Mountains of Tanzania. The approximate geographical coordinates are between latitudes 7° 00’ and 7°11’23.5”S and longitudes 37°30’ and 37°38’36.6”E, (Figure 2-1). The watershed covers an area of approximately 75610 km^2. The Uluguru Mountains, which make part of the Eastern Arc Mountains form the main headwaters of the Ruvu River Basin.

The rainfall distribution pattern is bi-modal with the main rainy season from March to May (MAM) locally known as the *masika*, and the short rains usually start in October and end in December (OND) locally known as the *vuli*, which is mainly controlled by the global circulation patterns. The bimodal pattern is usually associated with the northward and southward movement of the Intertropical Convergence Zone (ICTZ) and the El Nino-Southern Oscillation (ENSO) or other oceanic or atmospheric signals as well as the topography. Mean annual rainfall in the study watershed as observed from 1956 to 2012 ranges from 728 mm at the Morogoro Water Department station to 2450 mm at the Mondo station.

The high altitude areas receive more rainfall than the foothills and lowlands. Lowlands immediately adjacent to these mountains are characterized by less precipitation and high evapotranspiration rates, which often result in negative water balance. Temperature in the study area is variable with the mean monthly temperature ranging from 17.4° C (July) to 22.4° C (December).

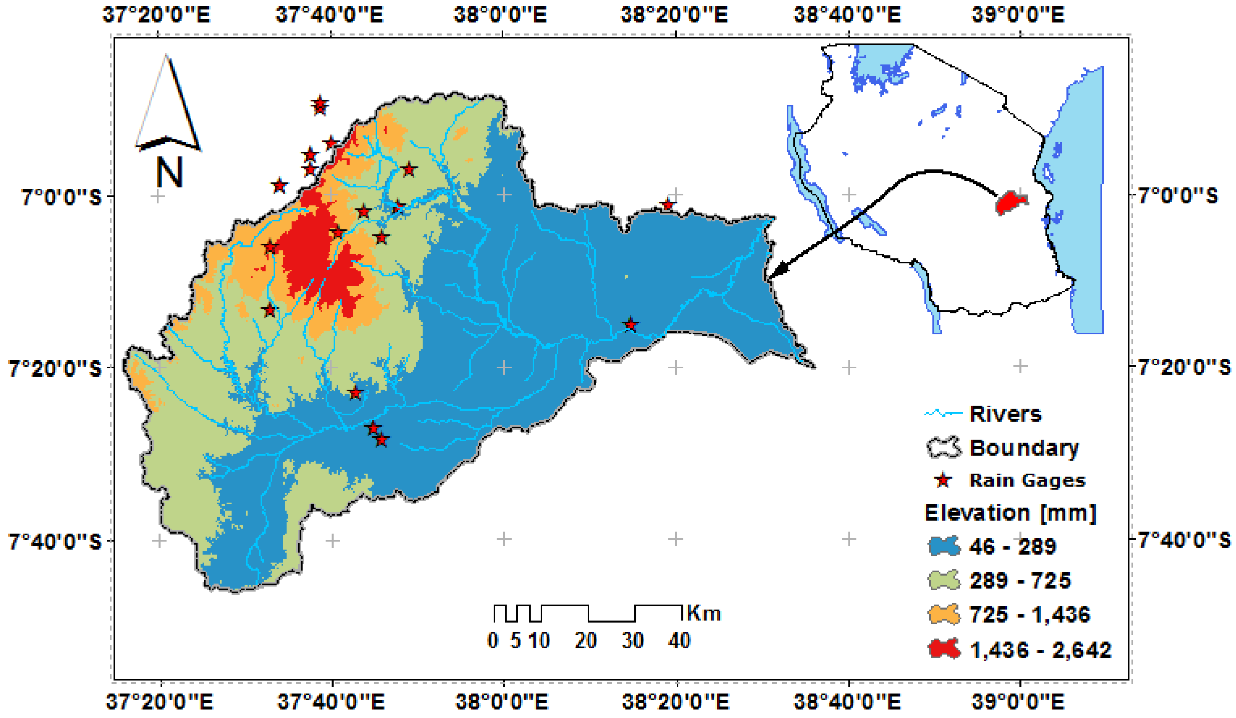

Figure 2- 1. Map of the Upper Ruvu watershed showing location, elevation, river network system and Rain gauge locations.

2.2.2 Methodology

Satellite imagery and ancillary data

Landsat data of the years 1991, 2000 and 2015 for path/row 167/65 and 166/65 were acquired from the Earth Explorer database of the US Geological Survey (http://earthexplorer.usgs.gov/). The time periods were chosen based on Landsat imagery availability. All the images were collected in the dry period **(Table 2-1**) in order to minimize the influence of weather variability on the analyses. LULC analyses in tropical countries are often affected by cloud cover, and therefore classification accuracy is usually affected by timing of data acquisition, and analysis period is chosen based on data availability. Clouds and shadows are common in the forested part of the Uluguru Mountains, such that cloud-free images are rare to find. In this study, it was not possble to obtain two scenes for a single date for 2015 which were cloud free. Therefore, a composite image for 2015 was made from six images of the two scenes. Seven bands were used for the imagery analysis with all at a ground resolution of 30 m.

Table 2- 1. Landsat data used in the study watershed

Satellite	Acquisition date	% Cloud Cover
Landsat 5	June, 5, 1991	2%
Landsat 7	July, 07, 2000	5%
Landsat 8	June-Aug, 2015	<10%

Image processing and classification

Pre-processing is usually done to make sure that every pixel in the image records the same type of measurement at the same location over time (Lunetta, 1998; Kennedy *et al.*, 2009). A total of 50 well distributed ground control points (GCPs) were used in the rectification process and the root mean square varied from 0.2 to 0.5 pixels. A first-order polynomial fit was applied and the data were resampled to a 30 m spatial resolution using the nearest neighbour method and projected to the Universal Transverse Mercator (WGS 84) coordinate system (Zone 37 South).

Classification scheme and and LULC cover classes

For LULC classification, eight thematic classes, excluding cloud cover and shadow, were identified to represent the prevailing situation on the range of cover types and associated land uses and management across spatial and temporal scales (Table 2-2) based on the reflectivity behaviour of the different classes (spectral signatures) and based on higher resolution imagery available from Google Earth, field assessments and literature review of publications (Burgess *et al.*, 2002; Yanda and Munishi, 2007; Lopa *et al.*, 2012). The classification scheme is based on the one recommended by Anderson (1976). The scheme represents coarse data aggregates corresponding to basic land management practices occuring in the Upper Ruvu River watershed and the Uluguru Mountains in general.

LULC classification in this study was done using the Random Forests (RFs) algorithm (Breiman, 2001). Random Forests (RFs) is an ensemble machine learning techniques which applies bootstrap aggregatation (bagging) and random feature selection to individual classification or regression trees for prediction (Breiman, 2001), and is increasingly being used for image classification and creation of continuous variables (Horning, 2010). The algorithm uses results from many different models to calculate a response (Horning, 2010). Several studies have reported the superiority of the RFs algorithm (e.g.,Breiman, 2001; Palmer *et al.*, 2007; Horning, 2010; Rodriguez-Galiano *et al.*, 2012). To date, several open source and commercial implementation for RF model development exist (Liaw and Wiener, 2002; Witten and Frank, 2005; Horning, 2012). In this study, the Random-Forest package (Horning, 2012) within the statistical software R 3.2.2 was used. Important common parameters required for running RFs include input training data and response variables, number of trees to be built, number of predictor variables to be used to create the binary rule for each split and parameters used to calculate information related to error and variable significance (Liaw and Wiener, 2002; Horning, 2010).

As a rule of thumb, the number of training samples is at least ten times the number of variables used in the classification to be considered sufficient (Richards and Richards, 1999; Jensen, 2005). In this study, a total of 886 training polygons with at least 100 pixels each were created and used in the study for the 2015 image. The polygons were selected randomly in the imagery but ensured good distribution in space and land cover classes. The highest numbers of training polygons were given to croplands and woodlands which had 174 and 112 training polygons respectively and distributed in different parts of the imagery. About 783 and 1081 training polygons were created for the 2000 and 1991 imagery, respectively. The choice of the training polygons for different cover types was based on the combination of field information, high resolution imagery (from Google Earth, IKONOS) of the study area.

The training polygons were converted to shape files and exported to the random forest model along with the stack of the Landsat images. It was difficult to discriminate various classes based on their spectral signatures from the Landsat imagery, due to the inherent heterogeneity in the area. Other indices representing different variables were therefore incorporated and used. These include, the normalized difference vegetation index (NDVI) to represent the phenology in vegetation, the normalized difference water index (NDWI) for water segregation, the tasseled cap for brightness, wetness and greenness, and elevation. In total 13 bands representing NDVI, NDWI, the three tasseled cap bands, elevation and the seven Landsat bands were made for each of the three time periods and used as input in the model. Procedures for data preparation were carried out in Erdas Imagine and ArcGIS, while the random forest model was run in R software.

Table 2- 2. LULC Classification scheme for the Upper Ruvu Watershed.

Type	Description
Forests	These are natural forests found in reserved areas of Uluguru montane forests and other protected areas with a canopy cover over 90%. Other areas include along rivers and in steep slopes and plantations.
Bushland	Dominant vegetation lower than 3 m but higher than 1m with a canopy cover above 10%, or dominant vegetation below 1m with a canopy cover above 50%. Often traversed by animal tracks.
Cropland and settlement	Areas currently under crop or land being prepared for growing crops. Areas with permanent concentration of man-made structures, people and activities such as villages and rural areas.
Woodland	All wooded areas with tree cover > 60%. Closed stands of trees.
Grassland	Open grassland/herb found in flat areas, grasses around the river banks in which water-table is at or near the surface, extensive livestock areas
Bare land	Non-vegetated/sparsely vegetated areas such as bare rocks, hard pans, where soil exposure is obvious
Water	Rivers, ponds and water reservoirs
Wetland	Flooded shrubland and reed beds dominated by bushes and grasses
Clouds and shadow	Areas covered with clouds and cloud shadows

Classification accuracy assessment and change detection

Accuracy assessment for the 2015 classification was performed based on data collected in the summer of 2014 and 2015 and Google Earth imagery for the time period. A total of 450 points were collected for the eight land cover classes. A stratified sampling approach was used in collecting reference data for accuracy assessment. Each land cover class was treated as a strata and reference data were collected randomly within the strata from different parts of the watershed. Apart from the reference data collected from the field, additional data from high resolution imagery within the Google Earth platform were used. Due to lack of field observations at the time of the earlier images, visual interpretation of the raw landsat images were used for the 2000 and 1991 images. This method has been reported in other studies for example Biro *et al.* (2013) and Sulieman (2008).

An error matrix or confusion matrix is a widely used way to represent thematic accuracy (Congalton, 1991; Congalton, 2001; Congalton and Green, 2008). In total, four measures of accuracy were produced for assessing accuracy: overall accuracy, kappa (*K*), producer's accuracy and user's accuracy. The producer's accuracy shows the probability that a pixel location of a land use class is correctly shown on the map, while the user's accuracy shows the probability that a pixel location on the map correctly identifies the land use class location as it exists in the field (Story and Congalton, 1986). Overall accuracy is an indication of the correctness of the map and is calculated by dividing the total number of correctly classified points by the total number of points

$$\text{Overall Accuracy} = \frac{\sum_{i=1}^{n} C_i}{N} * 100\% \qquad (2\text{-}1)$$

where C is the number of correctly classified points of the particular land cover and N is the total number of points. The Kappa coefficient is a measure of classifier performance derived from the error matrix but which is free of any bias resulting from chance agreement between the classifier output and the reference data (Richards and Richards, 1999; Campbell and Wynne, 2011). Kappa provides information about the map quality and its value ranges from -1 to 1.

Change detection is a useful method of satellite based remote sensing and involves finding the type, amount, direction and location of land cover changes occuring in an area (Yeh and Li, 1996). Following the classification of imagery from the individual time periods, a post-classification (Singh, 1989) comparison algorithm was used to determine changes in land cover in three time intervals, 1991-2000, 2000-2015 and 1991-2015. Post-classification comparison has been used successfully in other studies for detecting LULC change (Mas, 1999; Lu *et al.*, 2004; Peterson *et al.*, 2004; Shalaby and Tateishi, 2007; Dewan and Yamaguchi, 2009; Kashaigili and Majaliwa, 2010; Lu *et al.*, 2012). The percentage cover of LULC for the different covers was computed using the following formula:

$$\%LULC = \frac{Area_{it+1} - Area_{it}}{Area_{it}} * 100\% \qquad (2\text{-}2)$$

where A_{it} = area of cover i at the first date, and $Area_{it+1}$ = area of cover i at the next date.

2.2.3 Assessment of Soil Erosion Risk

The Revised Soil Loss Equation (RUSLE) (Renard *et al.*, 1991; Renard *et al.*, 1997) was used to calculate annual soil loss. The RUSLE equation is given as:

$$A = R*K*LS*C*P \qquad (2\text{-}3)$$

where: A is the average soil loss produced by water erosion per unit area (Mg $ha^{-1}y^{-1}$) at a particular point, R is the erosivity factor caused by rain (MJ mm $ha^{-1}h^{-1}$), K is the erodibility factor of the soil (MghMJ^{-1} mm^{-1}), LS is the slope length and steepness factor, C is the cover and management factor, and P is the support practices factor. In this study all the factors were considered to be spatially constant for a grid size of 30m. Information for each factor was calculated and interpolated using the Inverse Distance Weighted (IDW) method to make a raster for each factor at every cell/point in the wateshed.

Rainfall Energy factor (R)

Rainfall energy or erosivity refers to the capacity of rain to erode soil particles (Wischmeier and Smith, 1978). R factor (Wischmeier, 1959) can be calculated as a function of the total rainfall kinetic energy (E) and the maximum 30-minute rainfall intensity (I_{30}) known as the EI_{30} (Haan *et al.*, 1994) (Wischmeier and Smith, 1978; Morgan, 2009). The transport is then averaged over a time period, usually a year, in order to get the rainfall erosivity. Continuous rainfall records are necessary to calculate the maximum 30 minute rainfall intensity (EI_{30}). Due to lack of breakpoint rainfall to calculate rainfall intensity, Arnoldus (1977) proposed a modified fourier index F for use in R calculation which does not require the use of rainfall intensity. The index uses monthly and annual rainfall averages, which can easily be obtained in most areas. The F used in this study based on Arnoldus (1977):

$$F = \frac{\sum_{i=1}^{12} p_i^2}{P} \tag{2-4}$$

where pi is average monthly rainfall and P is average annual rainfall. Arnoldus *et al.* (1980) found a linear correlation between the F index and the Rainfall Erosivity factor (R). Based on the F, Renard and Freimund (1994) recommended an equation that can be used for calculating R for given F values greater than 55 mm:.

$$R = 95.77 - 6.081F + 0.4770F^2 \tag{2-5}$$

where R is the R-factor in (MJ mm $ha^{-1}h^{-1}$) and F is the Modified Fourier Index in mm.

Rainfall data for the study watershed were obtained from the Wami Ruvu Basin Water Board Office and the Tanzania Meteorological Agency. Rain gage network in the watershed is unevenly distributed with most gages found mostly around Morogoro town and in other populated areas in and around the watershed. There were 13 stations with monthly data ranging from 1990 to 2012 chosen and used in the study. The monthly average for the 23 year period was obtained for each rain gage station. The calculated R-factor values using Equation 2-5 are shown in Figure 2-2. The values range from 4496 to 34874 MJ mm $ha^{-1}h^{-1}y^{-1}$.

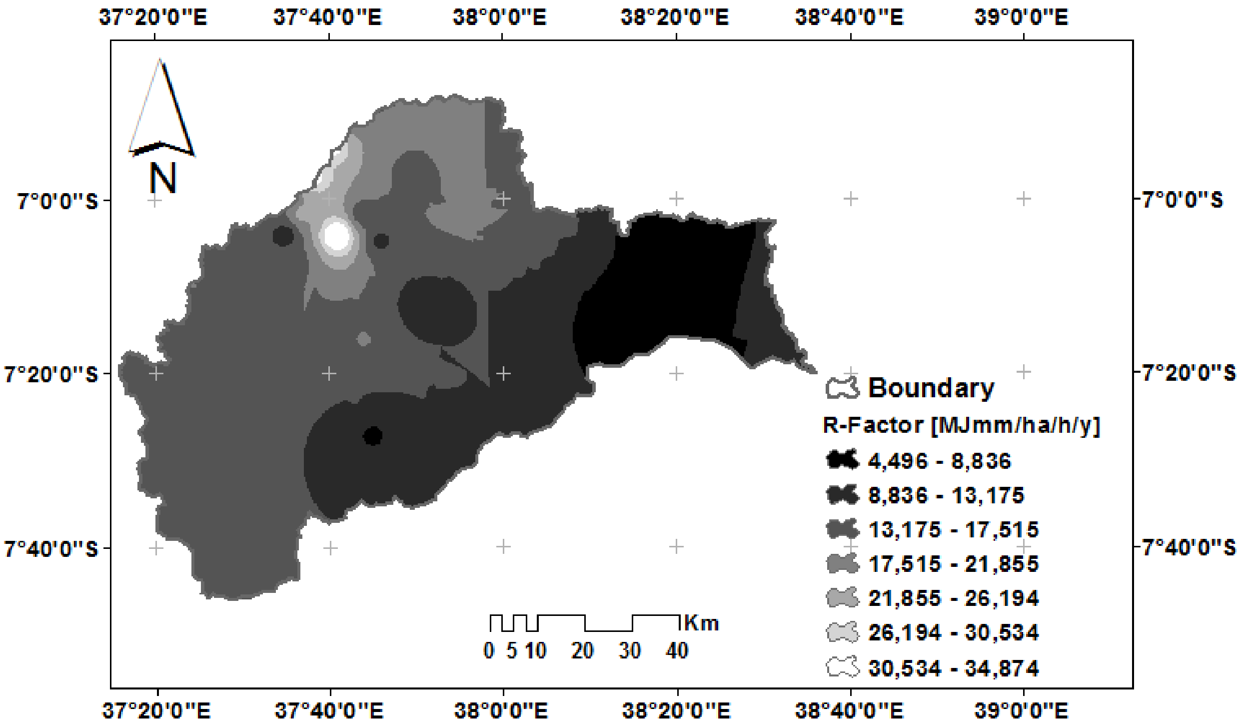

Figure 2- 2. Spatial distribution of R-factor values within the watershed

Soil sampling and soil erodibility factor (K)

Soil samples in the watershed were collected in the period from June – August, 2015 at the depth of 0-20 cm. A steel auger of 7 cm diameter was used for soil sample collection. A total of 22 samples were collected from sites representing different soil types. Each soil sample consisted of 2 to 6 sub-samples that were mixed to form a composite sample. These samples were taken from sites of different land use types. Slope, land use/cropping system, site and surface charateristics of each site were observerd and recorded at the site based on the National Soil Service of Tanzania, soil profile sheet. The soil samples were taken to the laboratory, where they were air dried and sieved through a 2-mm mesh. The hydrometer method (Bouyoucos, 1962) was used for determining soil particles' size distribution, and a wet sieving was used to determine the proportion of very fine sand. Humid oxidation using the Walkley-Black method (Soil Survey Staff, 2014) was used for determining the soil organic matter (OM). The permeability at each site was determined qualitatively in the field by evaluation of the soil horizons. Soil structure was also determined by physical evaluation in the field. The soil parameters were coded with the Wischmeier's nomograph (Wischmeier *et al.*, 1971). Soil information for other land use types and management where samples were taken, were extracted from the world soil grids by the ISRIC - World Soil information (ISRIC, 2013). The database carries world soils at six depths. For this study, soil information at the top 2 depths (0- 5 cm and 5 -15 cm) were averaged to obtain a single depth equivalent to the one used in the field collection.

The soil erodibility factor defines how susceptible soils are to erosion, representing the fact that various soils erode at different rates because of different physical characteristis such as texture, structure, and organic matter content. The K-factor was calculated using the equation suggested in Wischmeier and Smith (1978). As the equation comes in english units, conversion to SI units was done by dividing by 7.59 as suggested by (Renard *et al.*, 1997).

$$K = 0.277*10^{-6}*M^{1.14}*(12-OM)+(0.0043(s-2)+0.0033(p-3)) \quad (2\text{-}6)$$

where: K is the erodibility factor, OM is organic matter in percent, *s* represents structural parameter based on the first soil horizon, *p* is a permeability parameter and M is a function of the primary particle size fractions given by.

$$M = (\%\text{ very fine sand} + \%\text{ silt})*(100\text{-}\%\text{ Clay}) \quad (2\text{-}7)$$

As the Wischmeier monograph only shows OM values of up to 4% organic matter, values greater than 4% of OM were assumed to be equal to 4% (Ochoa-Cueva *et al.*, 2015). The K-factor values for each grid cell were calculated and are shown in Figure 6. The values range from 0.01 to 0.079, with a mean value of 0.04.

L and S factors

The effect of local topography on soil erosion rate in RUSLE is expressed by the LS factor, which is a combination of the effects of slope length (L) and slope steepness (S). A Digital Elevation Model of 30 m spatial resolution Shuttle Radar Topography Mission (SRTM) was downloaded from the USGS website (http://earthxplorer.usgs.gov) and processed by filling depressions and voids. The equation adopted for computing the LS factor (Mitasova *et al.*, 1996) is:

$$LS = (m+1)*[\frac{A_w}{22.13}]^m*(\frac{\sin\beta}{0.0896})^n \quad (2\text{-}8)$$

where A_w is the upslope contributing area per unit width of the contour width, β is the local slope (in radians), and m and n, are adjustable values depending on the soil's susceptibility to erosion. The values of the exponents vary in the literature, but m=0.4 and n=1.4 are the most commonly used values. These values were therefore chosen and used in this study. Slope gradient in degrees and flow accumulation were generated using ArcGIS®. The computed LS values ranged from 0 to 36.

Cover management C

The cover management is an important factor to be considered in the RUSLE equation as it denotes the human impacts on the environment as they interact and manage vegetation and soil, and the effect of vegetation growth stages on rainfall energy and soil loss (Haan *et al.*, 1994; Morgan, 2009). Apart from empirical values available in literature, remote sensing techniques such as the Normalized Difference Vegetation Index (NDVI) have successfully been used in some parts of the world (Karydas *et al.*, 2009; Tian *et al.*, 2009), including East Africa (Århem and Fredén, 2014; Jiang *et al.*, 2014) for estimating the C-factor. In this study, NDVI was derived from the Landsat imagery for each of the three years. A raster of C-factor based on NDVI for each time period was calculated using the equation given by Van Der Knijff *et al.* (1999).

$$C = \exp[-\alpha * \frac{NDVI}{(\beta - NDVI)}] \qquad (2\text{-}9)$$

where C is the calculated cover management factor, NDVI is the vegetation index, and α and β are scaling factors that denote the shape of the correlation curve of NDVI and C-factor. The raster of NDVI-derived C-factors was combined with the land use map to produce mean C-values for each land cover class. A raster of C-factors from literature (Morgan, 2009; Mulengera *et al.*, 2010) for each land cover class was prepared. Subsequently, the C-factors for each time period was calculated as an average of the mean C-factors and the corresponding C-factors from literature, and raster of C-factors for each land cover map were used for subsequent processes in the RUSLE equation.

Conservation Practices (P) Factor

The conservation practice factor describes the impacts of different practices implemented for land management to reflect the effect practices such as contours, terraces, strip crops and sediment basins. The practices could not be derived from the land use maps. It is also important to note that, apart from few areas with conservation methods and agroforestry introduced during the Payment for Watershed Ecosystem Services pilot project (Lopa *et al.*, 2012), and individual efforts by a small number of farmers in areas such as Mgeta, most areas remain without proper soil conservation measures. The P factor was assumed to be 1 for all three years.

2.3 Results and Discussion

2.3.1 Classification Accuracy

The accuracy assessment was performed using the 450 referenced points which were collected through stratified sampling. Error matrices were used for assessing classification accuracy of the maps based on the method by Congalton and Green (2008). Overall accuracies obtained were 93%, 91% and 93% for the 1991,2000 and 2015 images, respectively. The calculated Kappa indices of agreement for the three maps were 92%, 89% and 92% for 2015, 2000 and 1991, respectively (Table 2-3). The producer's accuracy (PA) which refers to the probability that a certain land cover of a place on the ground is classified, was between 89% and 100% for all land cover classes.The user's accuracy (UA)which refers to the probability that a pixel characterized as a certain land cover class in the map is really in the class, was between 81% and 99% for all land cover classes. Based on the overall accuracy and Kappa coefficient, the classified maps achieved a satisfactory classification accuracy. Anderson (1976) and Foody (2002) suggested that a good classification map should possess accuracy of at least 85 percent.

Table 2- 3. Accuracy Assessment of Classified Land Use and Land Cover Maps

Land Cover	1991		2000		2015	
	PA	UA	PA	UA	PA	UA
Natural Forest	95	95	89	98	99	97
Shrubland	91	91	93	89	94	91
Cropland and Rural Settlement	91	86	92	92	91	87
Woodland	91	94	93	86	94	97
Grassland	97	98	89	88	92	95
Bareland	99	96	94	86	92	88
Water	93	81	96	88	95	81
Wetland	97	99	87	95	96	98
Clouds and shadows	100	99	98	98	89	91
Overall Accuracy	**93**		**91**		**93**	
Kappa Coefficient	**91**		**89**		**92**	

2.3.2 Land Use and Land Cover (LULC) Maps for 1991, 2000 and 2015 and change detection

The land use and land cover maps for the three time periods, 1991, 2000, and 2015 were mapped for the watershed. Results show that forests and woodlands were dominant in 1991 and significant changes have occurred over time across the watershed. Figures 2-3, 2-4 and 2-5 reveal changing patterns of the land covers. While montane forests which are dominant up in the Uluguru Mountains have not changed much, other natural forests and woodlands in other parts of the watershed have been seriously disturbed from what used to be in 1991.

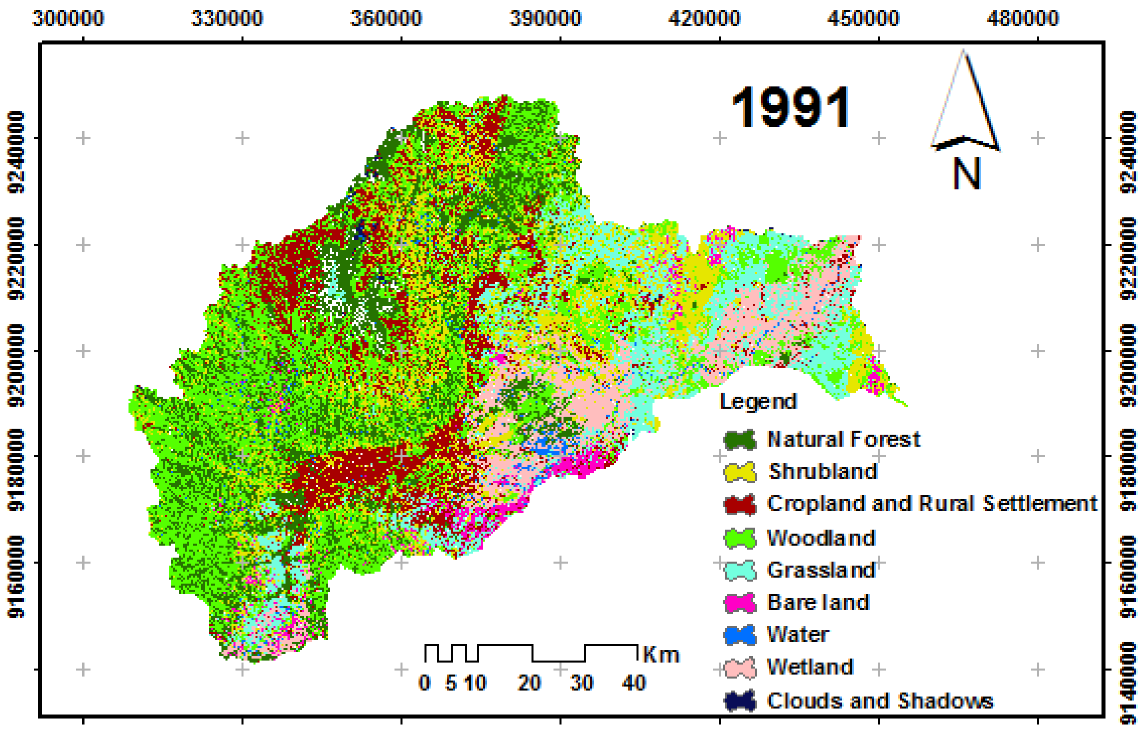

Figure 2- 3. Land use and land cover maps for 1991 for the Upper Ruvu Watershed

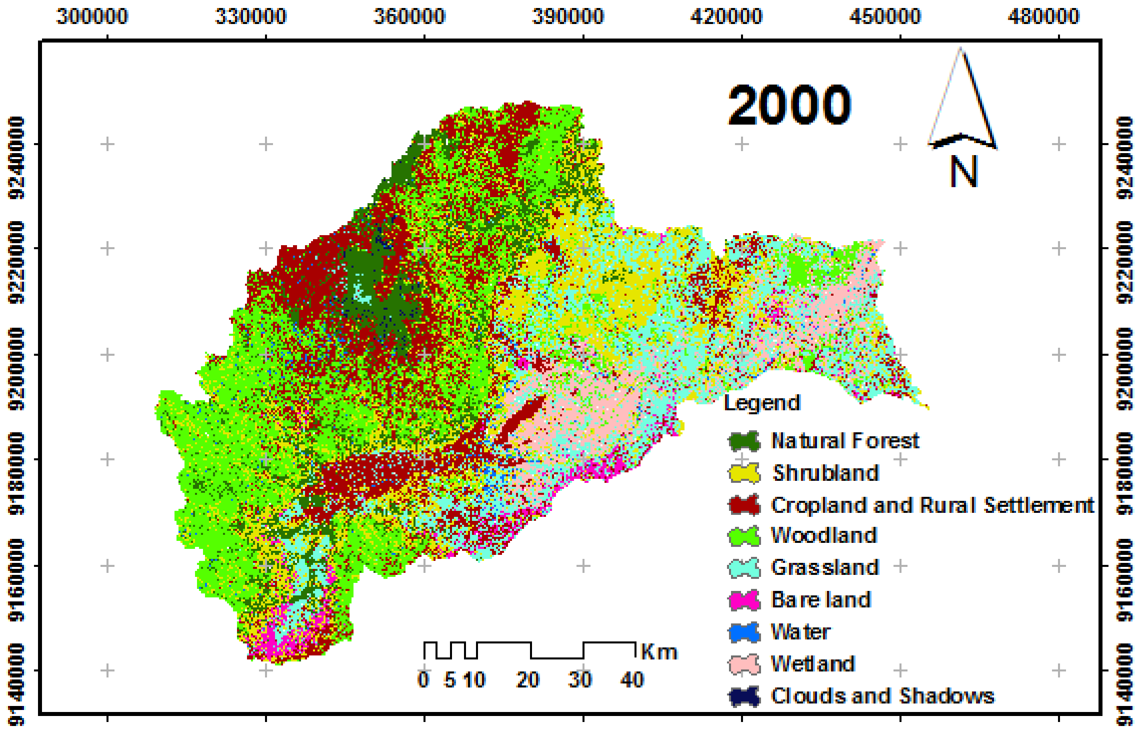

Figure 2- 4. Land use and land cover maps for 1991 for the Upper Ruvu Watershed

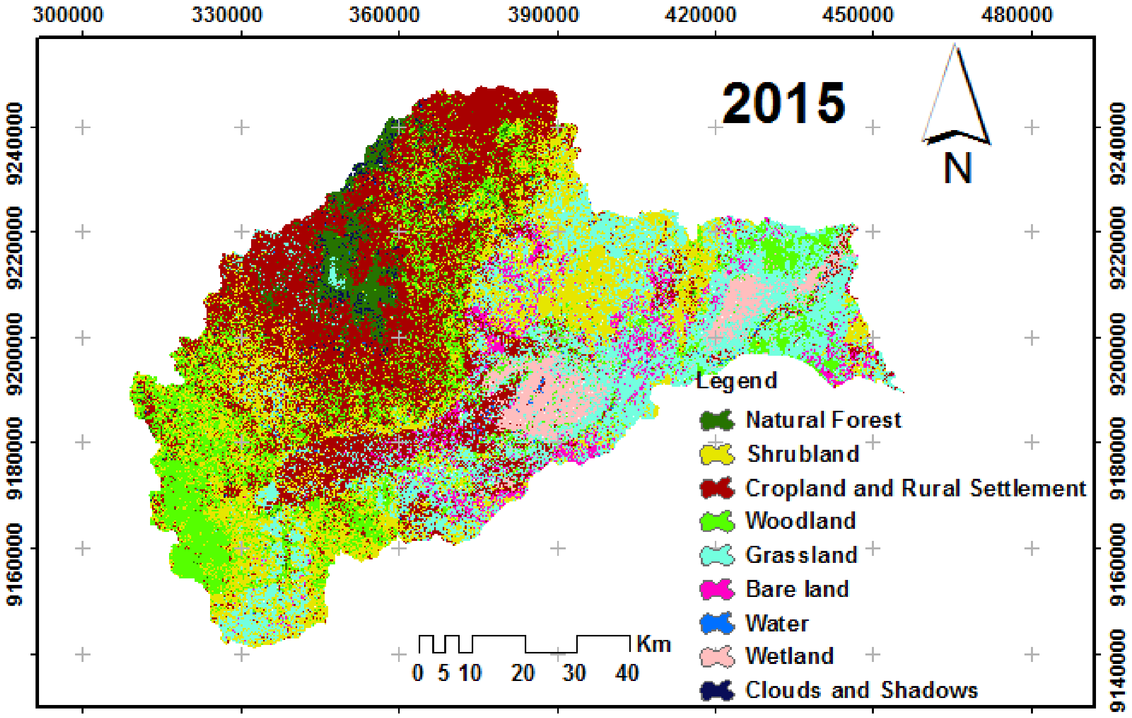

Figure 2- 5. Land use and land cover maps for 1991 for the Upper Ruvu Watershed

Natural forests in the watershed are concentrated in the natural reserves particularly on the Uluguru Mountains, and other forest reserves which are found in the eastern foothills of Kimboza, Ruvu, Mvuha/*Chamanyani* and Mkulazi (further east of the Ruvu river). Figure 2-3 shows that in 1991, natural forests were found in almost all areas in the eastern part of the watershed and riparian forests were common along the Ruvu and Mgeta rivers. However, as time progressed, most of these areas have either been reduced to shrublands, or have been converted into cropland and human settlement (Table 2-4). Woodland occupied the majority of the watershed with 29% of the total area in 1991, followed by natural forests which occupied 17% of the entire watershed area. Shrubland occupied 15% and cropland occupied 14% of the total watershed area. The percentage coverage of natural forests, woodland and wetland continued to decrease for the year 2000 (Figure 2-4) and 2015 (Figure 2-5). On the other hand, shrubland and grassland gained coverage for the 2000 and 2015 years, with more increase in grassland than in shrubland, occupying 15% and 20% of the entire watershed area for 2000 and 2015 respectively. The study also reveals loss of wetlands from 9% in 1991, to 4% in 2015, as most of this area was converted into cropland, mainly because of water availability for irrigation.

Table 2- 4. Land Use and Land Cover distribution for 1991-2015

Land use	1991		2000		2015	
	Area(Km^2)	%	Area (Km^2)	%	Area (Km^2)	%
Natural Forest	1289	17.2	767	10.2	295	3.9
Shrubland	1142	15.2	1385	18.4	1583	21.0
Cropland and Rural settlement	1048	14.0	1567	20.9	2216	29.4
Woodland	2171	28.9	1825	24.3	1212	16.1
Grassland	883	11.8	1142	15.2	1526	20.2
Bareland	177	2.4	176	2.4	284	3.8
Water	110	1.5	88	1.2	36	0.5
Wetland	668	8.9	545	7.3	332	4.4
Clouds and Shadows	15	0.20	17	0.2	68	0.9

Changes of land use in a 10-year period between 1991-2000 reveal a decrease of forests by 40%, and an increase of 50% of cropland. The results show a rapid shrinking of area covered by forests especially in the uplands. The decrease of forests and woodlands, and increases in croplands and grasslands was also noticeable for the period between 2000-2015. In general, there was an annual decrease of natural forests of approximately 4% and annual increase in cropland of approximately 5% between 1991 and 2015. Yanda and Munishi (2007), in a study involving the entire Ruvu basin reported a 25% decrease of forests and a 350% increase of cultivated land between 1995 and 2000. It is postulated that population increase in the landscapes of the watershed was responsible for the escalating land conversions. Comparison of population data from 2002 to 2012 show that population increased from 319,885 in 2002 to 433,421 in 2012. Figure 2-6 shows population increase pattern for some of the administrative wards in the watershed. Almost all wards experienced a surge in population, and increase of such activities as cutting trees for charcoal and firewood for rural households and for the urban population, and other activities was experienced.

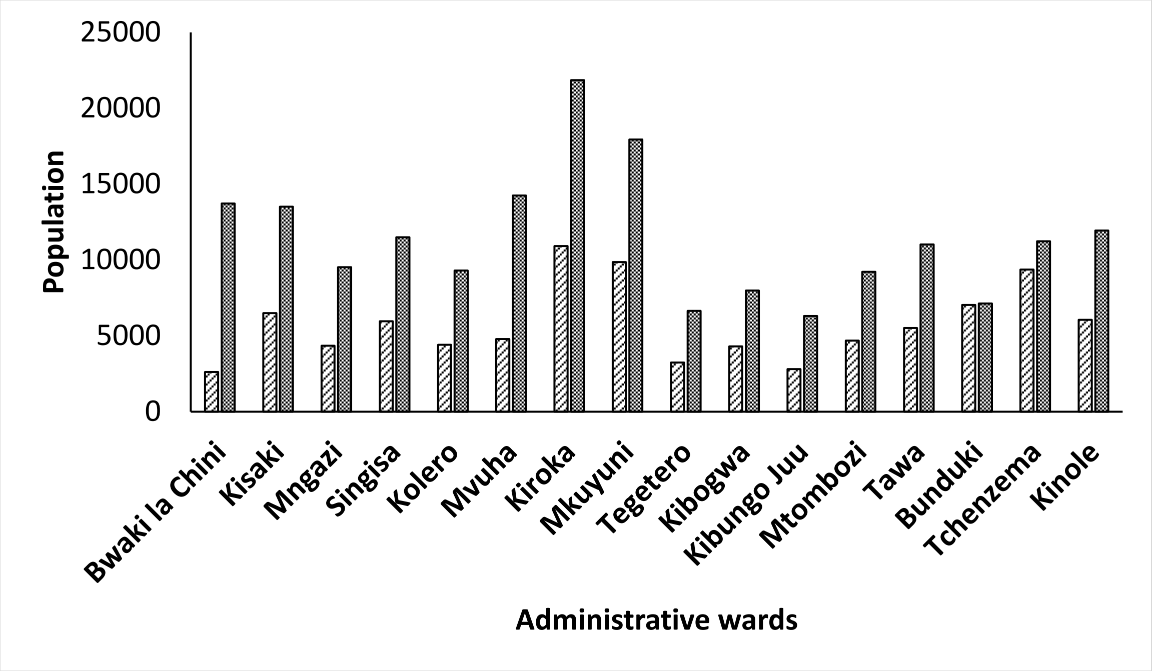

Figure 2- 6. Population increase of selected wards from 2002 to 2012 (Source: NBS, 2012)

2.3.3 Soil erosion estimation results

Results from the calculation of soil losses using RUSLE suggest that average soil losses over the entire watershed for 2000 and 2015 increased from the baseline period in 1991. There was an increase in the maximum and total soil loss for 2000 and 2015 as compared to the baseline year in 1991 (Table 2-6). Table 2-6 shows that the average annual soil loss was 6.4 t ha-1/year in 1991, 9.2 t ha^{-1}year^{-1} in 2000 and 14 t ha^{-1}year^{-1} in 2015 when evaluated for the entire watershed. These results show a 44% increase of soil loss from 1991 to 2000 and a 49% increase in soil loss from 2000 to 2015. The increase of mean values in the three time periods with other factors kept constant, varying only the land use factor shows that soil loss increased with increasing change in land use and land cover in the study area. The simulated average soil loss results for 2015 exceeds the tolerable values of 12t/ha/y (Milliman and Meade, 1983). In a study in the Mzinga watershed, which is located adjacent to the Upper Ruvu, but all located in the Uluguru Mountains, Mulengera *et al.* (2010) using USLE, reported average soil loss of 17 t/ha/yr. Maximum values of soil loss estimated increased from 45 t/ha/yr in 1991 to 53.3 t/ha/yr in 2000 and 79.8 t/ha/yr in 2015.

The greatest increase in soil loss was found in areas mostly dominated by cropland which increased by 26% and 82% for 2000 and 2015 respectively from the baseline time period in 1991 (Figure2-6). The increase was influenced by the expansion of cropland areas which increased from 1048 km^2 in 1991 to 2216 km^2 in 2015 (Table 2-3). Average soil loss from cropland areas increased from 19.8 t/ha/y in 1991 to 28.4 t/ha/y in 2015. From field measurements in the Mzinga River Catchment, which is located along the slopes of the Uluguru Mountains in the opposite side of the Upper Ruvu watershed, Mulengera *et al.* (2010) reported an average of 33 t/ha/y of soil loss from agricultural lands. The values of soil loss are lower compared to the values observed by Kimaro *et al.* (2008) using experimental plots in agricultural fields along the slopes of the Uluguru Mountains reported soil loss values of between 69 and 163 t/ha/yr. Nishigaki *et al.* (2016) using runoff plots conducted in maize fields reported soil loss values ranging between 15.9 t/ha/y to 47.2 t/ha/y. Using rainfall experiments on cropland,(Mbungu, 2016) reported mean soil loss values of between 11.1 and 18.9 t/ha/yr for gentle and steep slopes respectively. The values estimated in this study from the cropland areas fall within the values measured from the field and exceed the limits for sustainable utilization of land. The increase in soil loss is also evident in the estimated total amounts which were 218,822 t/y, 305,174 t/y and 481,986 t/y for 1991, 2000 and 2015 respectively. In other reported studies, Ligonja and Shrestha (2015) reported average annual soil loss between 14.7 and 23 t/ha/year in Kondoa, Dodoma, while Århem and Fredén (2014) reported 38-43 t/ha/year in Musoma, Tanzania. These studies, though from different landscapes and characteristics, help to define the confidence in our results. Some results, especially those obtained from experimental plots, are a bit higher compared to the results in the study watershed, but are within the range of results from other studies.

Table 2- 5. Soil loss estimates for the whole study area

Soil Loss	1991	2000	2015
Average (t/ha/y)	6.4	9.2	13.7
Minimum(t/ha/y)	0	0	0
Maximum (t/ha/y)	47.2	53.3	79.8
Standard deviation	34	49.6	68.9
TOTAL (t/y)	**218,822**	**305,174**	**481,986.4**

Figures 2-9 show the spatial distribution of soil loss in the watershed for 1991, 2000 and 2015. It can be observed that most of the soil loss is concentrated in the northern part of the watershed where cropland and other human activities are conducted on the steep slopes of the Uluguru Mountains. These areas are also characterized by high rainfall and soils susceptible to soil erosion. Out of six land cover classes (by excluding wetland, water, and clouds and shadows), forest had the least soil loss, with an annual average of 1 to 2 t/ha/year (Figure 2-7). Removal of vegetation cover as a result of deforestation on the slopes of the Uluguru Mountains contributes to the formation of crusts which facilitate runoff and limits infiltration of water into the soil. The increase in runoff and soil loss from the landscapes facilitate the removal of nutrients much needed for crop production in the area. The area covered by montane forest (Uluguru North and South Forest Reserves), although located in high precipitation and characterized by steep slopes experience lower values of soil loss. The presence of the forest help to protect the soil by providing high infiltration capacity and less runoff. This shows the contribution of the C-factor in estimating soil erosion with the RUSLE model. Areas within the same rainfall regime and topographical characteristics but with different C-factors (derived from the land cover) experienced different rates of soil loss. There was less soil loss from bare land for all the three time periods, which might have been due to its presence in the lowlands with low slopes and also low rainfall but was consistent with the change in area coverage. There was increase in soil loss from woodland, although the area covered by woodland decreased in 2000 and 2015.

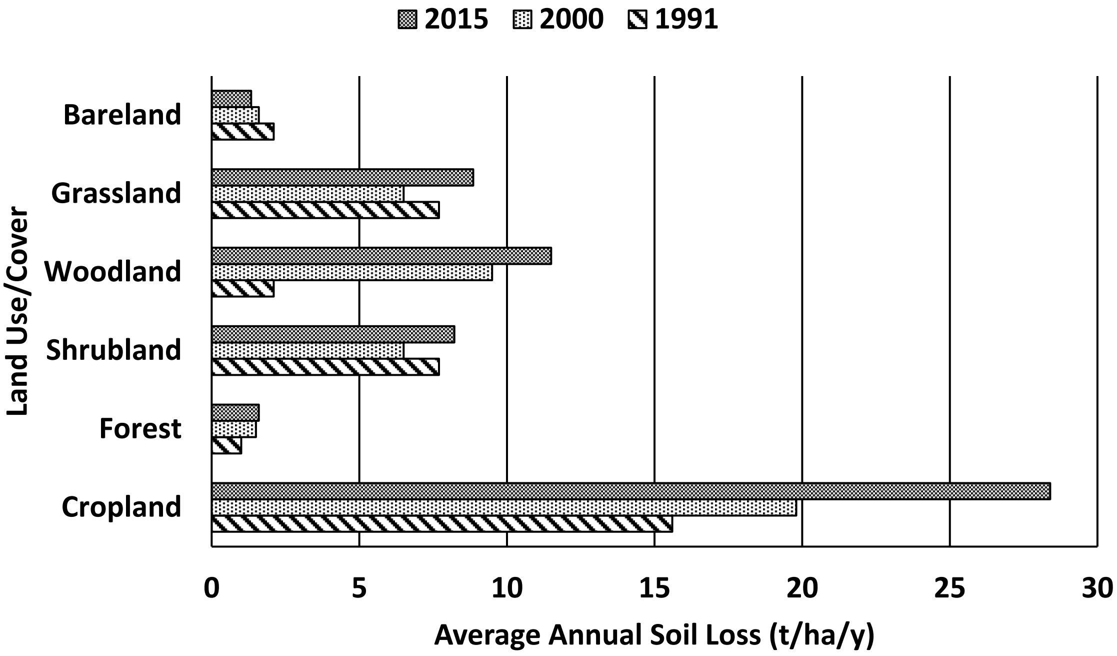

Figure 2- 7. Average soil loss per land cover class and year for selected land covers.

Based on estimated annual soil loss, the watershed was categorized into five erosion classes based on the severity of the soil loss. The classes are shown in Table 2-7 ranging from minimal (0-2 t/ha/year) to extreme (soil loss greater than 45 t/ha/year). Results show that, watershed areas in the minimal class decreased over time, and there is a consistent increase over time of the area under moderate to severe soil loss. The impacts of soil loss occuring in the moderate to extreme category constituting 20% of the watershed area can be overwhelming to the sustainability of the watershed. It is apparent that approximately 13% of the watershed is experiencing annual soil loss of more than 20 t/ha/year and 7.5% area in the extreme category are all above the threshold limit of 12 t/ha/y for sustainable landscapes. It is also worth noting that most of the soils eroded from the uplands are deposited in the foothills and lowlands and have off-site effects on the streams and rivers. Soil deposition was observed along river and stream reaches and farms in the lowlands.

Table 2- 6. Estimated soil erosion risk areas for 1991, 2000 and 2015

Erosion(t/ha/y)	Category	1991		2000		2015	
		Area (km^2)	%	Area (km^2)	%	Area(km^2)	%
0 – 2	Minimal	5631	75.4	4751	63.5	5035	66.6
2-10	Low	1013	13.6	1655	22.1	1007	13.3
10-20	Moderate	421	5.6	480	6.4	530	7.0
20-45	Severe	194	2.6	257	3.4	414	5.5
> 45	Extreme	212	2.9	334	4.4	350	7.5

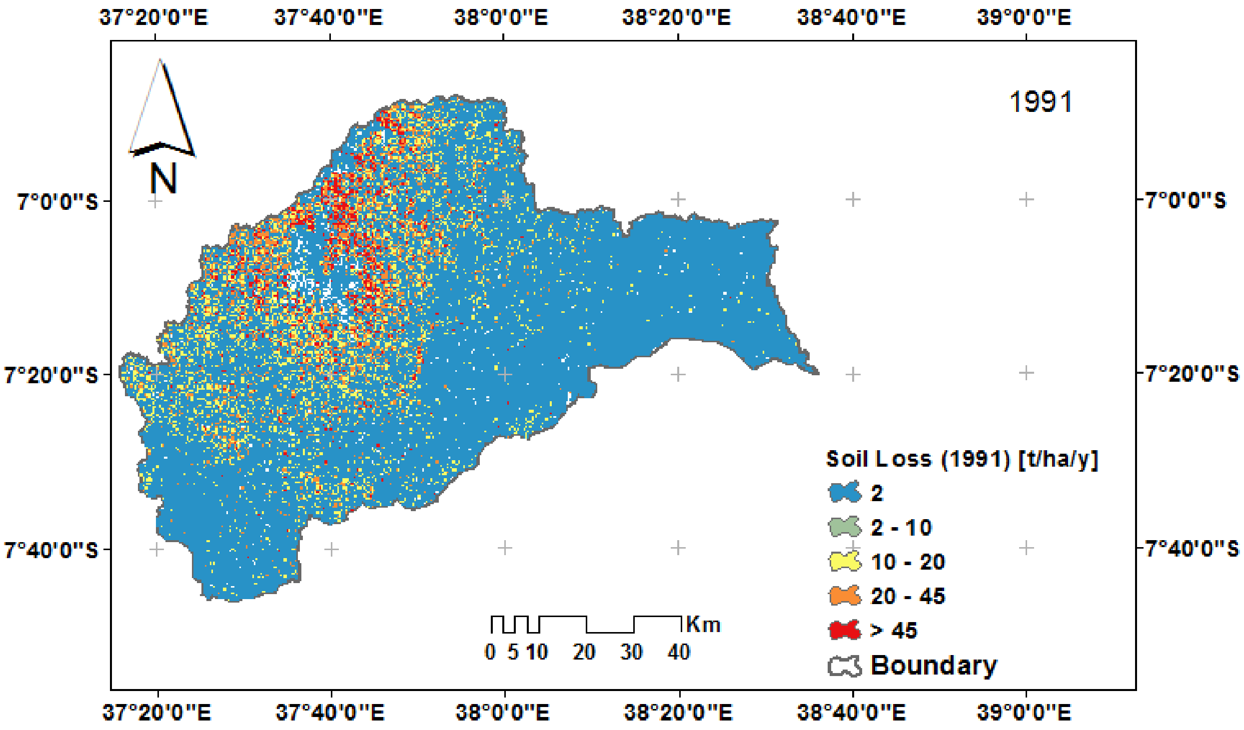

Figure 2- 8. Soil erosion risk map for the Upper Ruvu watershed for 1991

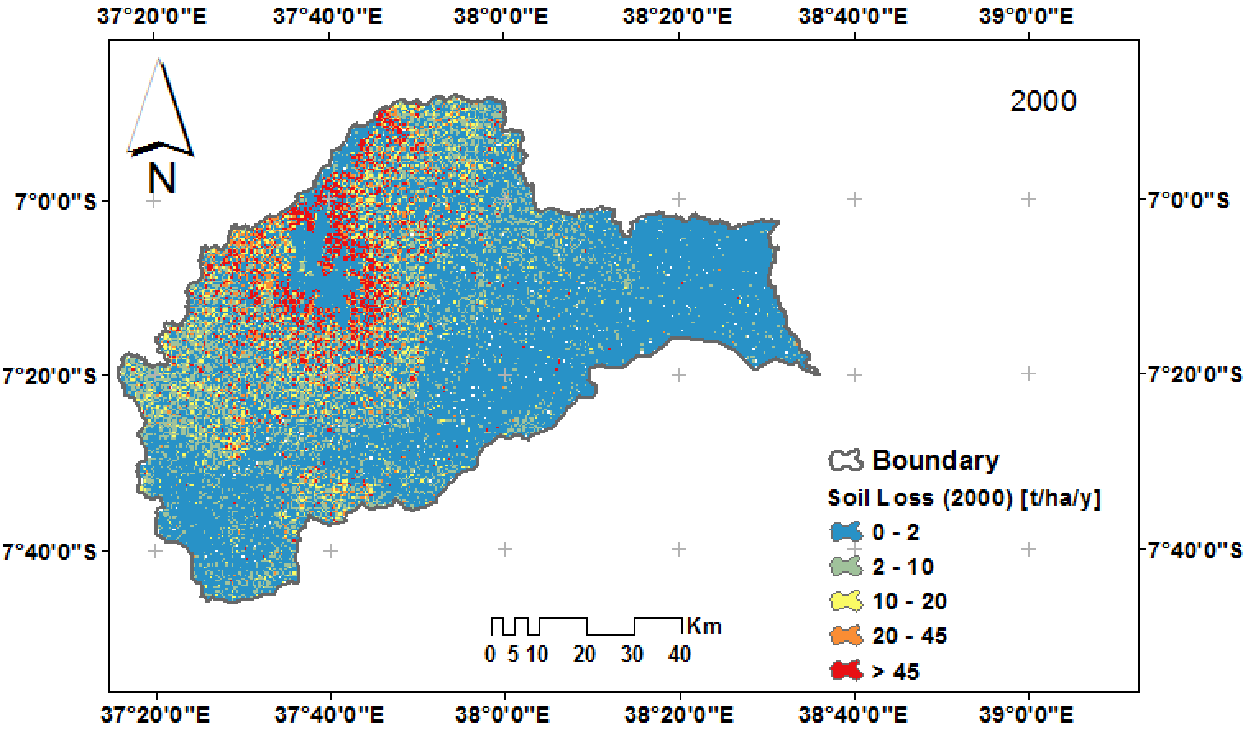

Figure 2- 9. Soil erosion risk map for the Upper Ruvu watershed for 2000

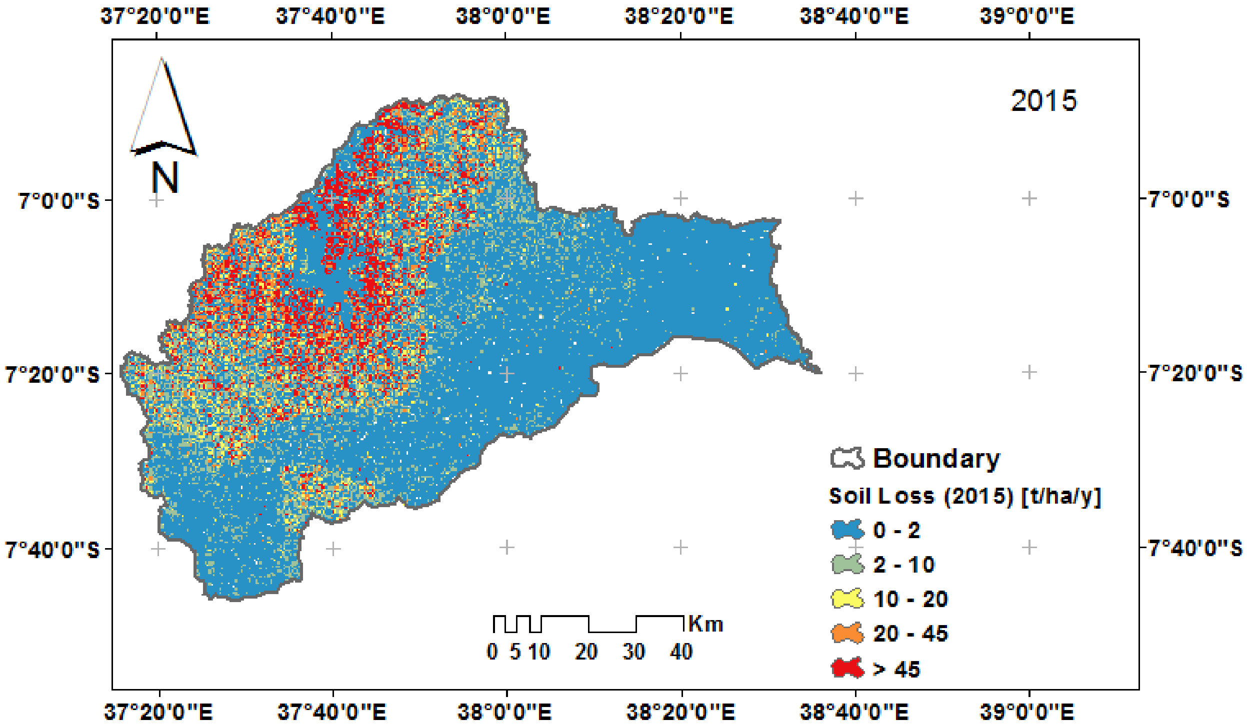

Figure 2- 10.Soil erosion risk map for the Upper Ruvu watershed for 2015

On examining further, the spatial distribution of soil loss, the watershed was delineated into 26 sub-watersheds based on the drainage systems as shown in Figure 2-10. This was intended to estimate the magnitude of soil loss in the most susceptible areas. The code SW signifies the watershed and the numbers are arranged from 1 to 26 overlaid on the 2015 soil loss map.

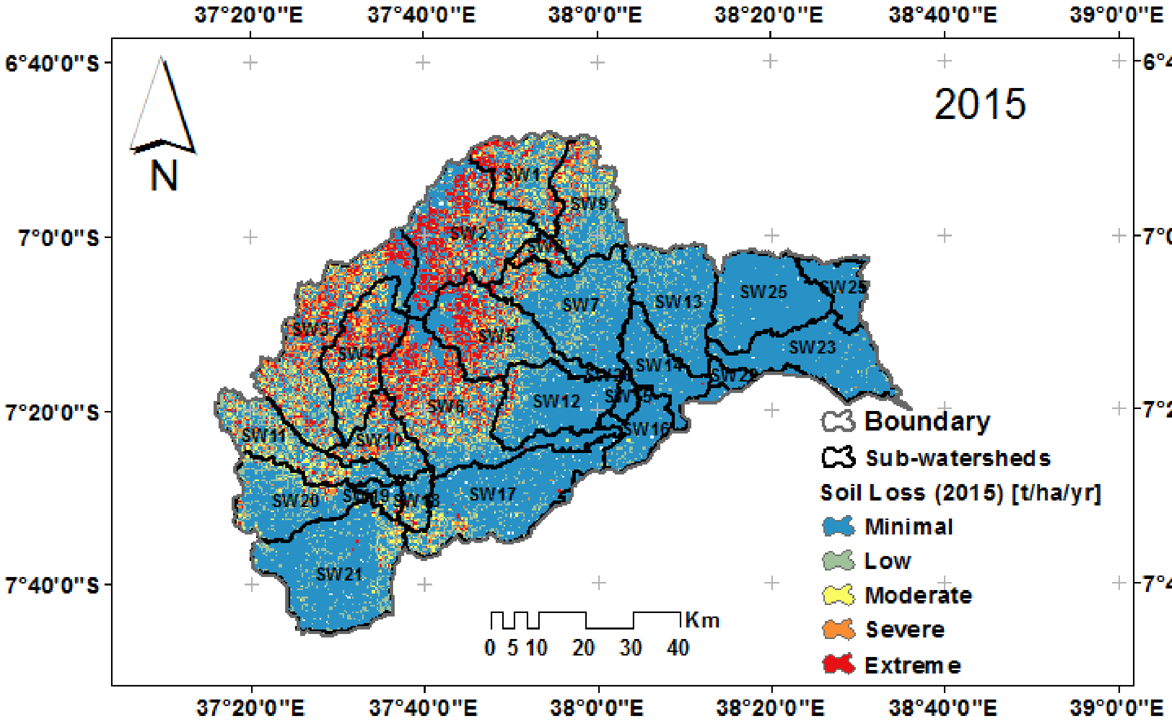

Figure 2- 11. Spatial distribution of soil erosion risks based on Sub-watersheds for 2015

Soil loss estimates based on sub-watersheds for selected twelve sub-watershed are shown in Table 2-8. Results show that the average soil loss based on sub-watersheds located in the uplands were high in sub-watershed number 2 (SW2) with a mean annual soil loss of 47 t/ha/year for 2015 increasing from 24 t/ha/year in 1991 (approximately 95% increase). This was followed by sub-watershed number 4 (SW4), sub-watershed number 5 (SW5) and sub-watershed 1 (SW1), all with increasing soil loss from the baseline period in 1991 to 2015. In general, sub-watersheds in the upstream part of the watershed fall into the moderate to extreme soil loss categories. To put this into perspective, SW1, which is known as the Kiroka/Maembe sub-watershed, SW2 known as the Kibungo Sub-watershed with its numerous tributaties (e.g. the Mfizigo, Mmanga and Mbezi rivers), SW3, SW4, and SW6 comprise the Mgeta sub-watershed, and sub-watershed SW5 known as the Mvuha sub-watersheds are the most susceptible to soil loss. These are dominantly cropland areas, which enjoy high rainfall and are all within steeper slopes than the rest of the watershed, apparently, they are the most populated as well.

Soil loss from the watershed in the uplands were examined and it was observed that the erosion was high in Kibungo watershed (SW2), Mgeta (SW2), Mvuha (SW5) and Kiroka (SW1), with 47 t/ha/year, 28 t/ha/year, 27 t/ha/year and 26 t/ha/year respectively for 2015. An increase of soil losses from 1991, 2000 and 2015 was consistent for all sub-watersheds. The results obtained in this study were compared with studies from similar environments. Mulengera *et al.* (2010) carried out a study in the Mzinga catchment using USLE equation and reported average annual soil losses of 17 t/ha/year. Kimaro *et al.* (2008) in their study in the opposite side of the Uluguru mountains carried out plot experiments in maize fields in varying slope steepness and reported average annual soil losses of 41 to 163 t/ha/year.

Table 2- 7. Average annual soil erosion losses (t/ha/year) and annual total losses (t/year) based on sub-watersheds

	1991		2000		2015	
Watershed	**Mean [t/ha/]**	**Total [t/ha]**	**Mean[t/ha]**	**Total[t/]**	**Mean[t/ha/]**	**Total[t/y]**
1	11.9	17067	16.5	23429	26.2	37782
2	24.0	67357	33.9	95474	47.0	133811
3	11.5	35019	15.8	47461	23.0	73198
4	11.2	19002	18.8	33275	28.3	50303
5	15.7	32713	19.8	42167	27.0	57648
6	7.8	25233	13.8	45596	19.0	63619
7	3.2	8212	3.7	9557	6.0	14251
8	13.3	4496	15.2	5124.5	20.0	6767
9	3.03	4707	7.4	7306	12.2	19236
10	5.2	5158.6	5.0	7691	17.1	16835
11	4.5	6970	5.5	8464	11.2	17485
12	2.0	3405	2.1	3759	3.4	6008

2.4 Summary and Conclusions

Land use and land cover (LULC) maps for the Upper Ruvu watershed were produced from Landsat imagery for three years (1991, 2000, 2015) to examine the changes in land cover over time. The use of random forest classification produced satisfactory results with Kappa accuracies of 92%, 89% and 92% for the 1991, 2000 and 2015 imagery, respectively.

The LULC maps provide the basis for evaluating the changes in land use and land cover for the last 25 years from 1991 to 2015. Area in cropland and rural settlement have increased, while natural forests decreased over the 25 year study period. Forest clearing is expected to primarily be for transition to agricultural activities but also occurs for activities such as for timber and building poles, and for charcoal and firewood production. In 1991, woodland was the largest land cover class with almost 30% of the total watershed area, but this decreased to only about 16% of the total watershed area in 2015. Natural forests which were scattered in most areas of the watershed, even in the foothills, eastern part of the watershed and in riparian areas, now are only concentrated in the reserve areas which are protected by the government. In some cases, illegal forest clearing for timber is happening inside the reserve areas threatening the sustainability of biodiversity. Most of the riparian vegetation has been cleared for cultivation, mostly because of water availability for irrigation and soil moisture for growing crops, especially horticultural crops during the dry season. Migration of people from other areas in search for land and water for irrigation, and pasture have escalated the land conversion problem. The population increase is exhibited by the significant change in population from 2002 to 2012. In addition, large herds of livestock are common in the foothills, and towards the eastern part of the watershed. Woodlands still dominate in the south-western part of the watershed, mostly because it is currently still not inhabited. In addition, areas that were dominated by wetlands are increasingly being used for agricultural purposes.

Soil loss assessment using the RUSLE equation reveal the risk of serious soil erosion in the uplands of the watershed. The calculated soil loss compares well with other studies using models and field measurements thus validating the RUSLE model. The average soil loss values increased with time from 6.4 t/ha in 1991, 9.2 t/ha in 2000 to 13.7 t/ha in 2015. Cropland, which has expanded to area of steep slopes are the most vulnerable to soil erosion with mean soil loss of 5.6 t/ha in 1991 to 28.4 t/ha in 2015. Areas most susceptible to soil erosion are found in the uplands and appear to be the most populated and mostly dominated by cropland. High values of soil loss estimated from 2015 appear to be consistent with the increase in human population (from 1991) and subsequent increase in cropland areas. The change in the C-factor has a major influence on soil erosion estimates and is a key factor for predictions of soil loss in the watershed. Comparison of soil loss for the three time periods shows the importance of vegetation cover for soil erosion reduction. High soil loss is prominent in the sub-watersheds located in the uplands, where higher rainfall, steeper slopes and agricultural lands are common. This suggests that soil conservation efforts targeting the areas most susceptible to soil erosion in the uplands are likely to contribute to better outputs towards reduction of soil erosion

The results in this study have shown that landscapes in the uplands of the Upper Ruvu watershed are subject to high soil erosion rates due to the pressure on forests exerted by human beings. Conservation of natural vegetation and proper agricultural and livestock management are needed as strategies to reduce soil erosion for sustainable environments. Further research on soil erosion parameters and field measurements of rainfall erosion targeting small areas are recommended for proper understanding of the influencing factors and for validation of the results from prediction models.

Acknowledgements

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References

Anderson JR. 1976. A land use and land cover classification system for use with remote sensor data. US Government Printing Office.

Århem K, Fredén F. 2014. Land cover change and its influence on soil erosion in the Mara region, Tanzania: using satellite remote sensing and the Revised Universal Soil Loss Equation (RUSLE) to map land degradation between 1986 and 2013. Student thesis series INES.

Arnoldus H. 1977. Methodology used to determine the maximum potential average annual soil loss due to sheet and rill erosion in Morocco. FAO Soils Bulletins (FAO).

Arnoldus H, Boodt Md, Gabriels D. 1980. An approximation of the rainfall factor in the Universal Soil Loss Equation. Assessment of erosion.: 127-132.

Bewket W, Teferi E. 2009. Assessment of soil erosion hazard and prioritization for treatment at the watershed level: Case study in the Chemoga watershed, Blue Nile basin, Ethiopia. Land Degradation & Development, **20**: 609-622. DOI: 10.1002/ldr.944.

Biro K, Pradhan B, Buchroithner M, Makeschin F. 2013. Land Use/Land Cover Change Analysis and its Impacts on Soil Properties in the Northern Part of Gadarif Region, Sudan. Land Degradation & Development, **24**: 90-102. DOI: 10.1002/ldr.1116.

Bouyoucos GJ. 1962. Hydrometer method improved for making particle size analyses of soils. Agronomy Journal, **54**: 464-465.

Breiman L. 2001. Random forests. Machine learning, **45**: 5-32.

Burgess N, Butynski T, Cordeiro N, Doggart N, Fjeldså J, Howell K, Kilahama F, Loader S, Lovett J, Mbilinyi B. 2007. The biological importance of the Eastern Arc Mountains of Tanzania and Kenya. Biological conservation, **134**: 209-231.

Burgess N, Doggart N, Lovett JC. 2002. The Uluguru Mountains of eastern Tanzania: the effect of forest loss on biodiversity. Oryx, **36**: 140-152.

Campbell JB, Wynne RH. 2011. Introduction to Remote Sensing. The Guilford Press.

Congalton RG. 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment, **37**: 35-46. DOI: http://dx.doi.org/10.1016/0034-4257(91)90048-B.

Congalton RG. 2001. Accuracy assessment and validation of remotely sensed and other spatial information. International Journal of Wildland Fire, **10**: 321-328. DOI: http://dx.doi.org/10.1071/WF01031.

Congalton RG, Green K. 2008. Assessing the accuracy of remotely sensed data: principles and practices. CRC press.

Dewan AM, Yamaguchi Y. 2009. Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization. Applied Geography, **29**: 390-401. DOI: 10.1016/j.apgeog.2008.12.005.

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK. 2005. Global consequences of land use. science, **309**: 570-574.

Foody GM. 2002. Status of land cover classification accuracy assessment. Remote sensing of environment, **80**: 185-201.

Gao X, Wu P, Zhao X, Wang J, Shi Y. 2014. Effects of Land Use on Soil Moisture Variations in A Semi-Arid Catchment: Implications For Land and Agricultural Water Management. Land Degradation & Development, **25**: 163-172. DOI: 10.1002/ldr.1156.

Haan CT, Barfield BJ, Hayes JC. 1994. Design hydrology and sedimentology for small catchments. Academic Press.

Horning N. 2010. Random Forests: An algorithm for image classification and generation of continuous fields data sets. In: Proceedings of the International Conference on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences, Osaka, Japan.

Horning N. 2012. Training Guide for Using Random Forests to Classify Satellite Images -v8. American Museum of Natural History. Center for Biodiversity and Conservation. Available from http://biodiversityinformatics.amnh.org. (accessed on 10/10/2015).

ISRIC. 2013. ISRIC - World Soil Information (2013). Available from http://www.soilgrids.org/. .

Jensen JR. 2005. Introductory digital image processing: A remote sensing perspective. Pearson College Division.

Jiang B, Bamutaze Y, Pilesjö P. 2014. Climate change and land degradation in Africa: a case study in the Mount Elgon region, Uganda. Geo-spatial Information Science, **17**: 39-53.

JICA. 2012. The Study on Water Resources Management and Development in Wami/Ruvu Basin in the United Republic of Tanzania. Ministry of Water (MoW).

Karydas CG, Sekuloska T, Silleos GN. 2009. Quantification and site-specification of the support practice factor when mapping soil erosion risk associated with olive plantations in the Mediterranean island of Crete. Environmental Monitoring and Assessment, **149**: 19-28.

Kashaigili JJ, Majaliwa AM. 2010. Integrated assessment of land use and cover changes in the Malagarasi river catchment in Tanzania. Physics and Chemistry of the Earth, Parts A/B/C, **35**: 730-741. DOI: http://dx.doi.org/10.1016/j.pce.2010.07.030.

Kennedy RE, Townsend PA, Gross JE, Cohen WB, Bolstad P, Wang YQ, Adams P. 2009. Remote sensing change detection tools for natural resource managers: Understanding concepts and tradeoffs in the design of landscape monitoring projects. Remote Sensing of Environment, **113**: 1382-1396. DOI: http://dx.doi.org/10.1016/j.rse.2008.07.018.

Kimaro DN, Poesen J, Msanya BM, Deckers JA. 2008. Magnitude of soil erosion on the northern slope of the Uluguru Mountains, Tanzania: Interrill and rill erosion. CATENA, **75**: 38-44. DOI: http://dx.doi.org/10.1016/j.catena.2008.04.007.

Lal R. 1998. Soil Erosion Impact on Agronomic Productivity and Environment Quality. Critical Reviews in Plant Sciences, **17**: 319-464. DOI: 10.1080/07352689891304249.

Lambin EF, Geist HJ, Lepers E. 2003. DYNAMICS OF LAND-USE AND LAND-COVER CHANGE IN TROPICAL REGIONS. Annual Review of Environment and Resources, **28**: 205-241. DOI: doi:10.1146/annurev.energy.28.050302.105459.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skånes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J. 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change, **11**: 261-269. DOI: http://dx.doi.org/10.1016/S0959-3780(01)00007-3.

Leh M, Bajwa S, Chaubey I. 2013. IMPACT OF LAND USE CHANGE ON EROSION RISK: AN INTEGRATED REMOTE SENSING, GEOGRAPHIC INFORMATION SYSTEM AND MODELING METHODOLOGY. Land Degradation & Development, **24**: 409-421. DOI: 10.1002/ldr.1137.

Liaw A, Wiener M. 2002. Classification and regression by randomForest. R news, **2**: 18-22.

Ligonja PJ, Shrestha RP. 2015. Soil Erosion Assessment in Kondoa Eroded Area in Tanzania using Universal Soil Loss Equation, Geographic Information Systems and Socioeconomic Approach. Land Degradation & Development, **26**: 367-379. DOI: 10.1002/ldr.2215.

Lopa D, Mwanyoka I, Jambiya G, Massoud T, Harrison P, Ellis-Jones M, Blomley T, Leimona B, van Noordwijk M, Burgess ND. 2012. Towards operational payments for water ecosystem services in Tanzania: a case study from the Uluguru Mountains. Oryx, **46**: 34-44. DOI: doi:10.1017/S0030605311001335.

Lu D, Mausel P, Brondízio E, Moran E. 2004. Change detection techniques. International Journal of Remote Sensing, **25**: 2365-2401. DOI: 10.1080/0143116031000139863.

Lu DS, Batistella M, Li GY, Moran E, Hetrick S, Freitas CD, Dutra LV, Sant'Anna SJS. 2012. Land use/cover classification in the Brazilian Amazon using satellite images. PESQUISA AGROPECUARIA BRASILEIRA, **47**: 1185-1208. DOI: 10.1590/S0100-204X2012000900004.

Lundgren L. 1978. Studies of Soil and Vegetation Development on Fresh Landslide Scars in the Mgeta Valley, Western Uluguru Mountains, Tanzania. Geografiska Annaler. Series A, Physical Geography, **60**: 91-127. DOI: 10.2307/520435.

Lunetta RS. 1998. Applications, project formulation, and analytical approach. Remote sensing change detection: Environmental monitoring methods and applications: 1-19.

Mas JF. 1999. Monitoring land-cover changes: A comparison of change detection techniques. International Journal of Remote Sensing, **20**: 139-152. DOI: 10.1080/014311699213659.

Mbilinyi B, Malimbwi R, Shemwetta D, Songorwa A, Zahabu E, Katani J, Kashaigili J. 2006. Forest area baseline for the Eastern Arc Mountains. Dar es Salaam: Forestry and Beekeeping Division, Ministry of Natural Resources and Tourism.

Mbungu W. 2016. Effect of land use on surface runoff and sediment yield under simulated rainfall in the Upper Ruvu watershed in Tanzania. Manuscript Chapter 4 in a PhD at Virginia Tech.

Milliman JD, Meade RH. 1983. World-wide delivery of river sediment to the oceans. The Journal of Geology: 1-21.

Mitasova H, Hofierka J, Zlocha M, Iverson LR. 1996. Modelling topographic potential for erosion and deposition using GIS. Int J Geogr Inf Syst, **10**: 629-641.

Morgan RPC. 2009. Soil erosion and conservation. John Wiley & Sons.

Msaghaa JJ, Melesse AM, Ndomba PM. 2014. Modeling Sediment Dynamics: Effect of Land Use, Topography, and Land Management in the Wami-Ruvu Basin, Tanzania. In: Nile River Basin, Springer, pp: 165-192.

Mulengera M, Lulandala L, Maliondo S. 2010. Soil erosion and sediment yield from the degraded Mzinga River Catchment in Uluguru Mountains, Tanzania. Tanzania Journal of Forestry and Nature Conservation, **79**: 47-57.

Muñoz-Rojas M, Jordán A, Zavala LM, De la Rosa D, Abd-Elmabod SK, Anaya-Romero M. 2015. Impact of Land Use and Land Cover Changes on Organic Carbon Stocks in Mediterranean Soils (1956–2007). Land Degradation & Development, **26**: 168-179. DOI: 10.1002/ldr.2194.

Mutua B, Klik A, Loiskandl W. 2006. Modelling soil erosion and sediment yield at a catchment scale: the case of Masinga catchment, Kenya. Land degradation & development, **17**: 557-570.

NBS. 2012. National Bureau of Statistics, Tanzania (NBS), 2012).Population and housing census: population distribution by administrative areas. Ministry of Finance, Dar es Salaam.

Ngoye E, Machiwa JF. 2004. The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Physics and Chemistry of the Earth, Parts A/B/C, **29**: 1161-1166. DOI: http://dx.doi.org/10.1016/j.pce.2004.09.002.

Nishigaki T, Sugihara S, Kilasara M, Funakawa S. 2016. Surface Runoff Generation and Soil Loss Under Different Soil and Rainfall Properties in The Uluguru Mountains, Tanzania. Land Degradation & Development: n/a-n/a. DOI: 10.1002/ldr.2499.

Ochoa-Cueva P, Fries A, Montesinos P, Rodríguez-Díaz JA, Boll J. 2015. Spatial Estimation of Soil Erosion Risk by Land-cover Change in the Andes OF Southern Ecuador. Land Degradation & Development, **26**: 565-573. DOI: 10.1002/ldr.2219.

Palmer DS, O'Boyle NM, Glen RC, Mitchell JB. 2007. Random forest models to predict aqueous solubility. Journal of chemical information and modeling, **47**: 150-158.

Peng T, Wang S-j. 2012. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. CATENA, **90**: 53-62. DOI: http://dx.doi.org/10.1016/j.catena.2011.11.001.

Peterson DL, Egbert SL, Price KP, Martinko EA. 2004. Identifying historical and recent land-cover changes in Kansas using post-classification change detection techniques. Transactions of the Kansas Academy of Science, **107**: 105-118.

Rapp A, Berry L, Temple P. 1972. Studies of soil erosion and sedimentation in Tanzania. Bureau of Resource Assessment and Land Use Planning, University of Dar es Salaam.

Renard KG, Foster GR, Weesies GA, McCool D, Yoder D. 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Agriculture Handbook (Washington).

Renard KG, Foster GR, Weesies GA, Porter JP. 1991. RUSLE: Revised universal soil loss equation. Journal of soil and Water Conservation, **46**: 30-33.

Richards JA, Richards J. 1999. Remote sensing digital image analysis. Springer.

Richter BD, Mathews R, Harrison DL, Wigington R. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. Ecological Applications, **13**: 206-224.

Rodriguez-Galiano V, Ghimire B, Rogan J, Chica-Olmo M, Rigol-Sanchez J. 2012. An assessment of the effectiveness of a random forest classifier for land-cover classification. ISPRS Journal of Photogrammetry and Remote Sensing, **67**: 93-104.

Schilling KE, Isenhart TM, Palmer JA, Wolter CF, Spooner J. 2011. Impacts of Land-Cover Change on Suspended Sediment Transport in Two Agricultural Watersheds. JAWRA Journal of the American Water Resources Association, **47**: 672-686. DOI: 10.1111/j.1752-1688.2011.00533.x.

Shalaby A, Tateishi R. 2007. Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. Applied Geography, **27**: 28-41. DOI: http://dx.doi.org/10.1016/j.apgeog.2006.09.004.

Singh A. 1989. Review Article Digital change detection techniques using remotely-sensed data. International Journal of Remote Sensing, **10**: 989-1003. DOI: 10.1080/01431168908903939.

Staff SS. 2014. Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 5.0. R. Burt and Soil Survey Staff (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service. Retrieved from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1253872.pdf (11 November, 2015).

Story M, Congalton RG. 1986. Accuracy assessment-A user\'s perspective. Photogrammetric Engineering and remote sensing, **52**: 397-399.

Sulieman HM. 2008. Mapping and modelling of vegetation changes in the Southern Gadarif Region, Sudan, using remote sensing: land-use impacts on biophysical processes. Zugl.: Dresden, Techn. Univ., Diss., 2007.

Temple PH. 1972. Soil and Water Conservation Policies in the Uluguru Mountains, Tanzania. Geografiska Annaler. Series A, Physical Geography, **54**: 110-123. DOI: 10.2307/520762.

Temple PH, Murray-Rust DH. 1972. Sheet Wash Measurements on Erosion Plots at Mfumbwe, Eastern Uluguru Mountains, Tanzania. Geografiska Annaler. Series A, Physical Geography, **54**: 195-202. DOI: 10.2307/520765.

Temple PH, Rapp A. 1972. Landslides in the Mgeta Area, Western Uluguru Mountains, Tanzania. Geografiska Annaler. Series A, Physical Geography, **54**: 157-193. DOI: 10.2307/520764.

Tian Y, Zhou Y, Wu B, Zhou W. 2009. Risk assessment of water soil erosion in upper basin of Miyun Reservoir, Beijing, China. Environ Geol, **57**: 937-942.

Van Der Knijff J, Jones R, Montanarella L. 1999. Soil erosion risk assessment in Italy. European Soil Bureau. Joint Research Center of the European Commission, 52p. Report.

Vanacker V, von Blanckenburg F, Govers G, Molina A, Poesen J, Deckers J, Kubik P. 2007. Restoring dense vegetation can slow mountain erosion to near natural benchmark levels. Geology, **35**: 303-306.

Wei W, Chen L, Fu B, Huang Z, Wu D, Gui L. 2007. The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China. Journal of Hydrology, **335**: 247-258. DOI: http://dx.doi.org/10.1016/j.jhydrol.2006.11.016.

Wischmeier W, Smith D. 1978. Predicting rainfall erosion losses: A guide to conservation planning U.S. Department of Agriculture

Wischmeier WH. 1959. A rainfall erosivity index for a universal soil loss equation. . Soil Science Society of America Proceedings, **23**: 246–249.

Wischmeier WH, Johnson C, Cross B. 1971. Soil erodibility nomograph for farmland and construction sites.

Witten IH, Frank E. 2005. Data Mining: Practical machine learning tools and techniques. Morgan Kaufmann.

WRBWO. 2008. Wami /Ruvu Basin Water Office (WRBWO). 2008. Business Plan.

Yanda P, Munishi P. 2007. Hydrologic and Land Use/Cover Change Analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) Watersheds. For WWF/CARE Dar es Salaam, Tanzania.

Yeh AG-O, Li X. 1996. Urban growth management in the Pearl river delta: an integrated remote sensing and GIS approach. ITC journal: 77-85.

Chapter 3. Correlate the Contribution of Climate Variability and Human Activities to Changes in Hydrology at Headwater and at Watershed Scale

Abstract

It is widely accepted that anthropogenic activities and climate variability have played a great role in hydrological changes in watersheds and ultimately affect quantity and quality of water resources. Hydrological responses to climate variability and human activities were investigated using three experimental watersheds (18-25 km^2 in size). Flow and suspended sediments fluxes were monitored for 2 years in the three small watersheds located in the uplands of the Upper Ruvu watershed (Morogoro Rural District). The watersheds are characterized by different land disturbances levels with the Mkungazi being the most disturbed (with 56% of the watershed area occupied by cropland and 38% by forests) followed by Kivumaga (61% of the watershed area occupied by forest and 39% by cropland) and Mbezi the least disturbed (72% of the area occupied by forest and 38% by cropland). Water yield was high and characterized by flashy response to rainfall in the most disturbed (Mkungazi and Kivumaga) compared to the least disturbed (Mbezi) watershed. High sediment loads were exported from the Mkungazi (284 t $km^{-2}y^{-1}$) and 230 t $km^{-2}y^{-1}$ for Kivumaga,) watersheds, whereas a much lower sediment loads were generated in the Mbezi watershed (117 t $km^{-2}y^{-1}$). The less disturbed watershed was characterized by high baseflow contribution to total flow and a low flashiness index compared to the two disturbed watersheds (Kivumaga and Mkungazi). Long term rainfall (1956-2012 and streamflow (1971-2012) data from 11 stations were analyzed to identify trends and changes in response to climate variation and anthropogenic activities. Analysis of annual and seasonal trends for the long term records at the watershed scale showed that rainfall had significant decreasing trends, with a change point in 1988. Streamflow showed non-significant decreasing trends. Changes in quantiles of daily rainfall and streamflow extremes displayed variability with positive and negative changes, with decreasing changes being more dominant. At an annual scale, climate variability contributed 46% and human activities contributed 54% of the changes in streamflow, signifying sensitivity of streamflow to human activities. The main human activities in the watershed with significant impacts to streamflow are related to land use change, which was significant from 1991 to 2015.

Key words: climate variability; headwater; human activities; rainfall; streamflow; suspended sediments; Upper Ruvu

3.1 Introduction

Evidence of changing mean and distribution of precipitation and temperatures have been documented around the world (Diffenbaugh *et al.*, 2005; IPCC, 2007; Singh *et al.*, 2014). Human activities in the form of land use change through deforestation and agricultural management (Milly *et al.*, 2005; Jiang *et al.*, 2011), along with climate variability have implications on the hydrology of river basins (Zhang *et al.*, 2008; Wang *et al.*, 2013) and are major drivers of river flow variability (Conway *et al.*, 2009). Climate variability refers to the seasonal or annual fluctuation of climate variables such as precipitation and temperature above or below long term averages. The variability in river flow and changes in hydrological regimes pose a challenge for water resources management with consequences on water supply and agriculture, especially in Sub-Saharan Africa, including Tanzania, where agriculture plays an important role in the economy and in the livelihood of more than 80 percent of the population (Ahmed *et al.*, 2011; Arndt *et al.*, 2012; Tumbo *et al.*, 2012).

The Uluguru Mountains in Morogoro Rural District are the headwater source of important tributaries such as the Mbezi, Mfizigo, Mmanga, Mvuha, Mgeta and other small tributaries that join downstream to form the Ruvu river. Streamflows in the Ruvu River have exhibited an overall decline in the past three decades (Ngoye and Machiwa, 2004; Yanda and Munishi, 2007; DAWASA, 2008) which can be attributed to the combined effects of climate variability and anthropogenic activities. Future projections, albeit with large degrees of uncertainty predict a decrease of up to 10% of flow in the Ruvu River (Mwandosya *et al.*, 1998; Noel, 2011). Moreover, conversions of natural forests and woodlands to croplands and grasslands for the last three decades have been reported (Yanda and Munishi, 2007; Mbungu and Heatwole, 2016a), and are likely to continue due to increase in population. Decreases in runoff could potentially result in serious impacts on socio-economic activities in Dar es Saalam, Morogoro and the Coast Region. Quantifying the effects and contribution of human activities and climate variability on hydrology is important for water resources assessment and management. This is especially important as water shortages in Dar Es Salaam and other areas that depend on the water from the Ruvu River have already been reported (IUCN, 2010; JICA, 2012). On the other hand, extreme tropical monsoon rainfalls in the long rainy season (March through May) and the short rainy season (October through December) have caused devastating floods in downstream areas in recent years (Baker, 2012). As environmental changes continue along with intensifying anthropogenic activities, understanding the processes and separating the contribution of climate variability and human activities is essential for water resources management, and identification of linkages between upstream and downstream interactions.

Due to the non-linear relationship among the factors causing changes on hydrological processes, understanding the contribution of each factor has been a challenge in hydrology (Jiang *et al.*, 2011; Wei *et al.*, 2013). A range of methods have been used in different parts of the world, ranging from experimental watersheds, field experiments, statistical analyses and hydrological modeling (DeFries and Eshleman, 2004; Li *et al.*, 2009; Elliott *et al.*, 2012; Fang *et al.*, 2012; Eshleman, 2013; Khoi and Suetsugi, 2014). While physically based hydrological models are powerful tools for analyses of impacts of environmental change on water resources, uncertainties related to structure, scale, calibration, parameters and extensive data requirements limit their application in data scarce areas, a familiar characteristic of watersheds in Sub-Saharan Africa (Conway *et al.*, 2009; Hughes *et al.*, 2015). Monitoring experimental (paired) watersheds has been used to assess how human activities in modifying the land surface have affected hydrological processes and other water quality and quantity constituents in watersheds (Wei *et al.*, 2013). Nonetheless, due to the resources, labor and time required for monitoring, only small number of experimental watersheds have been instrumented in Tanzania as typical in most Sub-Saharan countries (Hughes *et al.*, 2015). Monitoring efforts in the Wami-Ruvu River Basin, have not been focused towards small watersheds, such that few or none of the headwater watersheds are represented.

According to Milly *et al.* (2005), apart from climate which is manifested through precipitation and evapotranspiration, streamflow changes in a watershed can be affected by anthropogenic activities which may generate non-climatic changes. It is therefore important to determine any change-point due to non-climate changes and then use the period before as the baseline period to estimate the effect of climate variability (Jiang *et al.*, 2011). This knowledge is crucial for the planning, design and management of crucial water resources engineering structures, as the assumption of time-invariant statistical characteristics of hydro-climatological time series may not be valid following the increase in spatial extent and intensity of human activities and intensified global environmental changes (Chen *et al.*, 2007; Mbungu *et al.*, 2012; Tabari *et al.*, 2012; Eshleman, 2013). A review of methods focused on understanding the individual contributions of human activities and climate variability are presented in Wei *et al.* (2013). Common methods used include computing the impacts on every component of a water balance equation, regression analysis, runoff coefficient analysis (Wang *et al.*, 2013), sensitivity analysis (Dooge *et al.*, 1999; Milly and Dunne, 2002) and hydrological modeling (Wang *et al.*, 2010).

While there is evidence of rainfall and river flow variability at the Ruvu basin scale (Yanda and Munishi, 2007), no detailed studies have been carried to understand the variability in rainfall and streamflow at both sub-watershed and watershed scale. Moreover, little understanding exists on the contribution of human activities and climate on streamflow variability. Analyses of long term hydrological data can identify changes in runoff and also decipher the contribution of climate variability and anthropogenic activities. As the watershed and its resources are highly dependent by diverse resource users from the small-scale farmers in the upstream to downstream users in the city of Dar Es Salaam, proper management should be a high priority. Increase in the frequency of extreme rainfall events due to changing climate can result in severe losses to life and properties (García *et al.*, 2007).

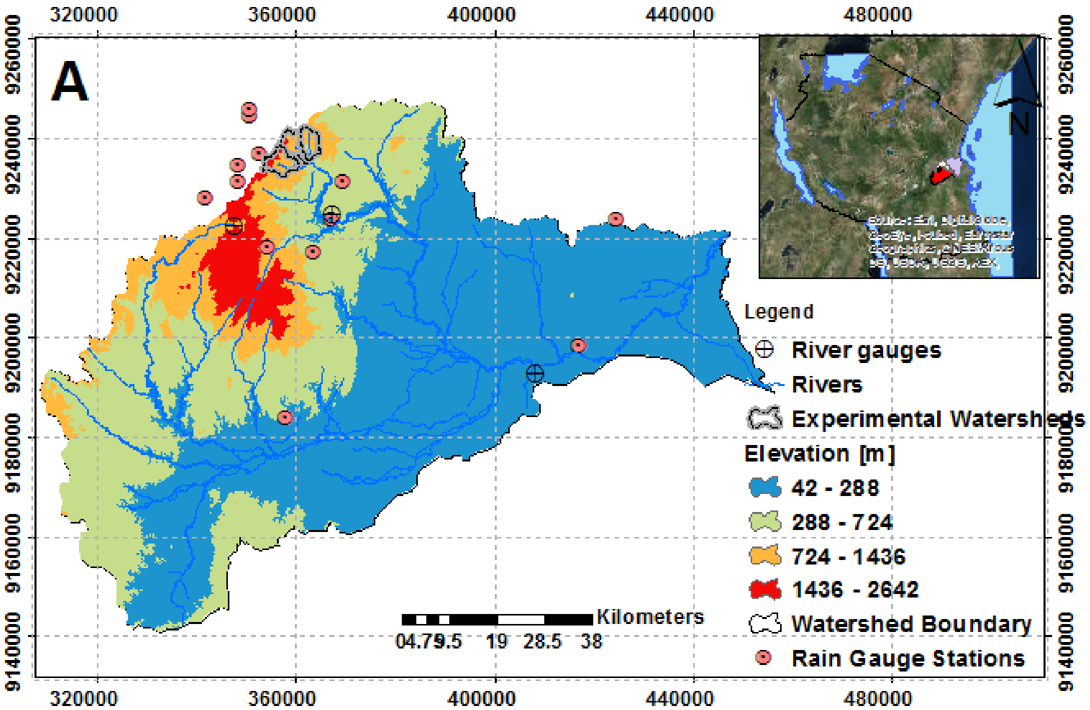
The objectives of this study were to i) assess temporal variation of streamflow and suspended sediment on three headwater watersheds, ii) determine trends and abrupt changes in long term precipitation and in streamflow records in the upper Ruvu watershed and detect extreme values in precipitation and streamflow, and iii) quantify contribution of climate variability and human activities on streamflow.

3.2 Materials and Methods

3.2.1 Description of the study area

This study was carried out in the Upper Ruvu watershed which is located within the Eastern Arc Mountains of Tanzania. The headwaters of the Ruvu River lie in the Uluguru Mountains. . The watershed lies approximately between latitudes 7° 00′ and 7°11′23.5″S and longitudes 37°30′ and 37°38′36.6″E (Figure 3-1). The Upper Ruvu River Watershed covers an an area of approximately 7510 km^2. Major tributaries are the Mgeta in the west, and Ruvu which comprises the Mvuha, Mmanga, Mfizigo and Mbezi in the east. The Ruvu River is an important source of water supply for Dar es Salaam city and coast region. Administratively, the watershed lies in the Morogoro Rural District in Morogoro region.

The mean annual rainfall in the study area ranges from 700 mm to 2450 mm. The rainfall distribution pattern is bi-modal with the main rainy season from March to May (MAM) locally known as the *masika*, and peak in April, whereas the short rains usually start in October and end in December (OND) locally known as the *vuli*, which are mainly controlled by the global circulation patterns. The bimodal pattern is usually associated with the northward and southward movement of the Intertropical Convergence Zone (ICTZ) and the El Nino-Southern Oscillation (ENSO) or other oceanic or atmospheric signals as well as the topography. Winds blowing from the Indian Ocean lose much of their moisture in the Uluguru Mountains in the form of orographic rain when they are forced to rise and undergo adiabatic cooling. The *La Nina winds* are responsible for drought in dry years. More rainfall is received in the high altitude areas than the foothills and lowlands. Lowlands immediately adjacent to these mountains have less precipitation. Temperature in the study area is variable with the mean monthly temperature ranging from 17.4° C (July) to 22.4° C (December).



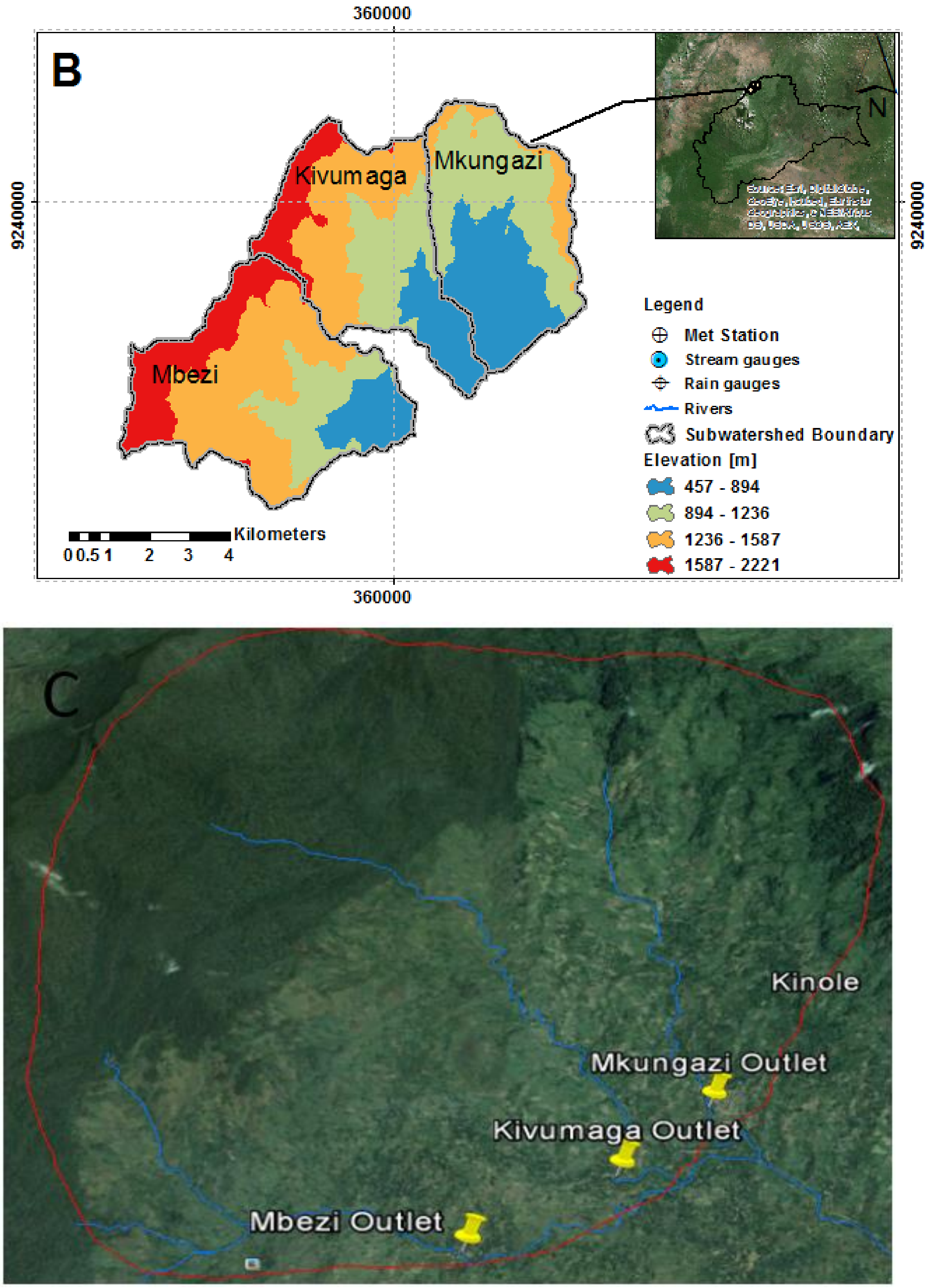


Figure 3 - 1. Map of the Study Area (A) showing the experimental watersheds and gauge sites (B and C)

3.2.2 Data description

Instrumentation of the experimental watersheds

The headwater watersheds located in the uplands of the Upper Ruvu Watershed were identified and characterized in January, 2014. The identification of the watersheds for instrumentation was done in collaboration with the Wami Ruvu Basin Water Office staff. The boundaries of each watershed were delineated using geographical information sytem (GIS) from the 30-m Digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM)(Farr *et al.*, 2007). The three tributaries forming the headwater watersheds are Mbezi, Kivumaga and Mkungazi which all join to form the Mbezi River downstream of the town of Kinole. The tributaries originate from the north-eastern part of the Uluguru North Forest Reserve, and are under forests, cultivation and human settlements. The Mbezi sub-watershed covers an area of 25.2 km^2, while the Kivumaga and Mkungazi cover areas of 19.6 and 18.5 km^2 respectively. The three sub-watersheds had different levels of human disturbances which were examined by quantifying the areas covered by forests and croplands, the two dominant land use types in the sub-watersheds. The percentage area covered by forest and croplands for the three sub-watersheds (Table 3-1) was determined from a land use map of the study area derived from 2015 Landsat imagery. Acrisols were the major soils dominant in all the three sub-watersheds. Based on the percentages of forest (combination of natural forests and woodland) and cropland it was found that the Mkungazi sub-watershed was the most disturbed, followed by Kivumaga, with Mbezi the least disturbed.

Table 3 - 1. Main characteristics of the Study sub-watersheds.

Watershed	Area (Km^2)	Main Land Use	Mean Elevation	%Mean Slope
Mbezi	25.2	Forest (72%) Cropland (38%)	1360	42
Kivumaga	19.6	Forest (61%) Cropland (39%)	947	43
Mkungazi	18.5	Forest (38%) Cropland (56%) Shrubland (6%)	1240	40

A monitoring program of climate parameters (rainfall, temperature, relative humidity, and solar radiation), streamflow and suspended sediments was developed and implemented in the three headwater small watersheds. The monitoring program started in January, 2014 and continued for two years. One automatic weather station was installed at Tegetero Mission to record rainfall, relative humidity, temperature, solar radiation and pressure. Two additional tipping bucket recording rain gages (0.2 mm/tip) were installed in Kinole and Nyange Primary Schools to record rainfall from about 1 m above the ground. Along every automatic rain gage station, a manual rain gage was also installed where local volunteers recorded data daily.

At each watershed outlet, a pressure sensor to record water level at 15 minute interval was installed along with a staff gauge. Data from the sensors were dowloaded at least every two months. Flow measurements were made using current meters in both the dry and wet seasons, with the aim of getting enough points to establish a stage-discharge relationship. In a few occassions, when wading was deemed unsafe, a float was used to estimate stream velocity and used with the established cross-sectional profile of the site. The rating curves of $r^2 = 0.995$ ($q = 15.149H^{1.8144}$), $r^2 = 0.9882$ ($q = 15.77H^{3.5428}$), $r^2 = 0.9546$ ($q = 15.024H^{2.9016}$) for Mbezi, Kivumaga and Mkungazi respectively were obtained for the stage-discharge relationships.

Rainfall data recorded from a rain gauge located at Nyange Primary School were excluded from further analysis because of data gaps due to vandalism of the instrument. Short-term failure in data acquisition from the other rain gages were corrected by replacing missing values with data from the manual rain gages located in the area. A heavy storm on November, 26, 2015 washed out the Mkungazi gage station, hence the data for Mkungazi station ends on that date.

Water samples for suspended solids were collected using grab samples and depth integrated sampler (DH-48). A weekly sample collection regime was carried out in the rainy season and a bi-monthly sediment sample collection during baseflow periods.

Long term data compilation

Long term daily rainfall data from nine stations with data ranging from 1956 to 2013 were obtained from the Wami Ruvu Basin Water Office (WRWBO) and from the Tanzania Meteorogical Agency (TMA). Location of the rain gage stations are shown in Figure 3-1. The rain gage network in the Upper Ruvu watershed is unevenly distributed with most gages found around Morogoro and in areas close to village centers and schools in and around the watershed and there were few stations in the foothills and some parts of the lowlands. Data collected were of different record length and some stations had many periods of missing data. A further look into the data archives showed that data collection and storage was consistent in the early 1950s up to the 1980s and less efficient thereafter, until recently when there has been a renewed focus on data gathering and monitoring. Quality checks were done to identify inconsistencies, erroneous entries, outliers and missing data. Regressions using nearby stations were used for filling missing data. Temperature, relative humidity, wind and solar radiation data for the Morogoro Meteorological station was obtained from the Tanzania Meteological Agency. Discharge data for Ruvu River at Mikula (1H10) were obtained from the Wami Ruvu Basin Water Office. Data collection was consistent in the early 1960s, 1970s, and 1980s, but data paucity occurred in the 1990s. A summary of the data used in the analysis are shown in Table 3-2. Missing data for streamflow records were filled by substituting with simulated data (SWAT model) for the study watershed (Mbungu and Heatwole, 2016).

Potential evapotranspiration ET_o was calculated using the Penman-Monteith Equation (Allen et al., 1998) expressed as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{3-1}$$

where ET_o is reference evapotranspiration (mm/day), Rn is net radiation (MJ $m^{-2}day^{-1}$), G is soil heat flux density (MJ $m^{-2}day^{-1}$), T is mean daily air temperature at 2 m height (^oC), u_2 is wind speed at 2 m height (ms^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), e_s-e_a

is saturation vapor pressure deficit (kPa), Δ is slope vapor pressure curve (kPa $^oC^{-1}$), γ is psychrometric constant (kPa $^oC^{-1}$). The equation has been implemented in the ETo calculator (Raes and Munoz, 2009), and was used for computing ET_o in this study.

Table 3 - 2. Stations in the Upper Ruvu Watershed

No	ID	Station	Latitude	Longitude	Altitude	MAR*(mm)	%Missing	Start	End
1	9637046	MorningSide	-6.9	37.67	1450	2217	2	1966	2014
2	9737076	Morogoro	-6.83	37.65	526	817	0	1971	2014
3	9737006	Matombo	-7.08	37.77	390	1547	11	1973	2014
4	9637045	Mondo	-6.95	37.63	1120	2384	3	1970	2013
5	9637048	Ruhungo	-6.92	37.63	880	979	0	1971	2010
6	9737026	Kibungo	-7.02	37.80	270	1519	12	1971	2013
7	9637052	Moro WD	-6.82	37.65	510	728	7	1956	2010
8	9000064	Mikula	-7.25	38.25	80	765	0.15	1976	2013
9	9737005	Singiza	-7.38	37.72	460	1325	9	1973	2007
10	9637047	Hobwe	-6.98	37.57	740	917	4	1971	2012
11	9637051	Mlali	-6.97	37.53	598	758	5	1956	2010

*MAR-Mean Annual Rainfall

3.2.3 Analysis of suspended sediment samples

Suspended solids concentration (SSC) was determined by gravimetric method. The water samples were vacuum filtered through a 0.45-µm filter and the residue oven dried at 105 °C for 24 h. The weight of each dried residue and the sample volume provided the SSC (g/l). Daily suspended sediment load (kg/day) was then calculated as the product of the SSC and mean daily flow.

An estimate of annual suspended sediment yield (SSY, tons) was calculated using the equation described in Duvert *et al.* (2010):

$$\mathrm{SSY} = \frac{0.3}{n} * \sum_{i=1}^{n} Q * \mathrm{SSC} \tag{3-2}$$

where SSY = Annual Suspended Sediment Yield (tons), Q= average daily streamflow (m^3/s), SSC is the suspended sediment concentration (g/l), and n is the number of samples in a year of 365 days.

3.2.4 Hydrological Analysis

Hydrographs from the three sub-watershed outlets were normalized by their corresponding watershed sizes for comparison among the three outlets. The calculation of the ratio of the total runoff to total rainfall for each sub-watershed was computed for each year and here is referred to as the runoff ratio (RR). Streamflow separation into baseflow and direct runoff was done based on a method by Hewlett and Hibbert (1967) as implemented in the Web GIS-based Hydrograph Analysis Tool (WHAT) using a recursive digital filter method of baseflow separation (Lim *et al.*, 2005; Lim *et al.*, 2010). This approach of hydrograph separation has been used in hydrological studies in forested and agricultural watersheds in tropical and temperate regions (Schwartz, 2007; Longobardi and Villani, 2008; Recha *et al.*, 2012). From the results of the hydrograph separation, the direct runoff ratio (RRDF) and the baseflow ratio (RRBF) were computed as the ratio of direct runoff to total rainfall and baseflow to total runoff, respectively. The baseflow index (BFI) (Bloomfield *et al.*, 2009), a ratio of baseflow to total flow was also computed. Furthermore, in order to examine the frequency and rapidness of streamflow in the three sub-watersheds, a flashiness index ($R\text{-}B_{index}$) was computed using the equation by Baker *et al.* (2004):

$$R - B_{index} = \frac{\sum_{i=1}^{n} \left| Q_i - Q_{i-1} \right|}{\sum_{i=1}^{n} Q_i} \tag{3-3}$$

where q_i and q_{i-1} are the daily streamflows (m^3/s) at time steps i and i-1 respectively, and n is the number of observations. According to Baker *et al.* (2004), the flashiness index exhibits low interannual variability and better detects trends in streamflow regimes. The flashiness index has been used to investigate streamflow response to changes in land use and forest conversions in East Africa in Kenya (Recha *et al.*, 2012), and in Ethiopia (Tekleab *et al.*, 2014). In order to compare the differences in flows (high, median and low) across the watersheds, cumulative flow duration curves (on a probability axis) were calculated (Vogel and Fennessey, 1995).

3.2.5 Long term trend detection

Mann-Kendall trend detection in rainfall, ET_o and Streamflow

Monotonic trends in the annual and seasonal rainfall series were assessed using the Mann-Kendall test. The Mann-Kendall (Mann, 1945; Kendall, 1975) is a non-parametric test that has been widely used for identification of long-term trend in hydrometeorological time series (Hamed, 2008; Tabari *et al.*, 2012; Wei *et al.*, 2013; Zhang *et al.*, 2014; Tabari *et al.*, 2015; Wang *et al.*, 2015). The Mann-Kendall is based on the statistic, S, which is calculated by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{3-4}$$

where x_j and x_i are the sequential data values, n is the length of the data set and sgn(x) is the sign function that is equal to 1, 0, -1 if x is greater than, equal to, or less than zero respectively.

The null hypothesis H_o is that there is no trend in the dataset, that S is approximately normally distributed with a mean zero. For data sets with more than 10 values, the variance associated with the statistic S (Var(S)) can be calculated as:

$$\operatorname{var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{3-5}$$

The values of S and Var(S) are used to compute the test statistic Z as follows:

$$\text{z} = \begin{cases} \dfrac{\text{S-1}}{\sqrt{\text{va(S)}}}, & \text{if S} > 0 \\ 0, & \text{if S} = 0 \\ \dfrac{\text{S+1}}{\sqrt{\text{var(S)}}}, & \text{if S} < 0 \end{cases} \tag{3-6}$$

The presence of a statistically significant trend is evaluated using the Z value. Positive and negative values of Z indicate an increasing and decreasing trends, respectively. The statistic Z has a normal distribution. H_o can be rejected as the significance level of α if $|Z| \geq Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables (Liu *et al.*, 2014). The slope of the trend was calculated by applying the Theil-Sen estimator (Sen, 1968). The trend of autocorrelated time series was estimated following Yue *et al.* (2002).

3.2.6 Quantile Perturbation approach for extreme rainfall and streamflow

Extreme value analysis deals with the extreme deviations of variables from the mean or probability distributions. It involves time-dependent parameters such as rainfall and discharge in order to reflect possible temporal departures in the frequency distribution. Many studies that have documented changes in rainfall and streamflow have done so through analysis of annual and monthly mean values. Despite its importance for human livelihoood and socioeconomic develoment, examination of changes in extreme rainfall and streamflow have been rare, mostly due to the lack of good quality daily rainfall data. Daily rainfall data collated as part of this study were obtained from the Wami Ruvu Basin Office (WRBWO) and the Tanzania Meteorological Agency (TMA) and were first quality checked graphically by JICA (2012), and in this study a thorough check of accuracy was done using both graphical and statistical approaches such as double mass curve. In this study variability in precipitation extremes were analyzed using the quantile pertubation method (QPM). The method includes use of frequency analysis and calculation of change factors which are hereafter referred to as the pertubations. The temporal trends in historical time series and cycles are revealed after applying the method to several time blocks, which are then combined to exhibit the temporal variation of extreme changes. Details of the methods are described in Ntegeka and Willems (2008), Willems (2013) and Mbungu *et al.* (2012). The method has been used for assessing trends in hydro-climatic extremes in the Nile Basin and Belgium (e.g. Mbungu *et al.*, 2012; Onyutha and Willems, 2015). Monte Carlo simulation was applied to the time series to derive bounds of variability using the 95% confidence interval. In this study, anomalies were analyzed for the two rainy seasons March-May (MAM) and October-December (OND) using a 5-year time block.

3.2.7 Change Point Analysis and Double Mass Curves

A sequential Mann-Kendall test (Sneyers, 1991) was used for change point detection of significant change in the time series. The test sets up two series, a forward series (here is referred as CF and a reverse series (referred here as CB). The test statistic S_m is defined as:

$$S_m = \sum_{i=1}^{m} \sum_{j=1}^{n} \theta_{ij} (m = 2,3,4,....,n) \tag{3-7}$$

$$\theta_{ij} = \begin{cases} 1 & x_i > x_j \\ 0 & x_i \le x_j \end{cases} \quad 1 \le j \le i \tag{3-8}$$

The sequential values of the statistic CF are calculated from the following equation:

$$CF = \frac{S_m - E(S_m)}{\sqrt{var(S_m)}} \tag{3-9}$$

In which

$$E(S_m) = \frac{m(m-1)}{4} \tag{3-10}$$

$$E(t_j) = \frac{j(j-1)}{4} \tag{3-11}$$

$$var(S_m) = \frac{1}{72}[m(m-1)(2m+5)] \tag{3-12}$$

CF follows the standard normal distribution, which is the forward statistic sequence, and the backward sequence CB is calculated using the same equation but with a reversed series of data.

In the two sided test, if the null hypothesis rejected, an increasing (CF>0) or a decreasing (CF<0) trend is indicated. If there is a match point of the two curves and the trend of the series is statistically significant, the match point would be regarded as the change point.

Consistency of the rainfall and runoff data were visually investigated using double mass curve (Kliment and Matoušková, 2009). A straight line signifies that the data are consistent, and changes in the gradient may indicate that the characteristics of rainfall or runoff have changed. The deviation point is usually the change point. In this study, the method was used along with the sequential Mann-Kendall to confirm the change point of rainfall and runoff time series.

3.2.8 Estimating the impact of climate variability on streamflow

Impacts of the variability of the climate variables in streamflow was investigated through hydrological sensitivity analysis. Long-term hydrological sensitivity here is defined as the percentage change in mean annual streamflow, Q, occurring as result of change in mean annual rainfall P and potential evapotranspiration ET_o. The change in mean annual runoff can be determined using the expression (Koster and Suarez, 1999; Milly and Dunne, 2002).

$$\Delta Q_{clim} = \beta \Delta R + \alpha \Delta ET_O \tag{3-13}$$

Where ΔQ_{clim} is the changes in streamflow caused by climate variability, ΔR and ΔET_o are change in rainfall and potential evapotranspiration respectively; β is the sensitivity of streamflow to rainfall and α is the sensitivity to potential evapotranspiration.

The coefficients β and α can be expanded as:

$$\beta = \frac{1+2x+3wx}{(1+x+wx^2)^2} \tag{3-14}$$

$$\alpha = \frac{1+2wx}{(1+x+wx^2)^2} \tag{3-15}$$

where x is the aridity index equal to ET_o/R, w is the plant-available water coefficient, which represents the relative difference in the way plants use soil water for transpiration. While the value of x was calculated from the relationship of potential evapotranspiration and rainfall, the value of w for different land cover types was estimated following Zhang *et al.* (2001). The w parameter values of 2 were assigned for forests and woodland (where cover > 50%), 1 for shrubland and grasslands, 0.5 for croplands and 0.1 for bare lands. The β coefficient for different land use types was calculated and the aggregate value for the mixed land uses in the watershed was calculated using the relationship suggested by Sun et al., (2005):

$$\beta = \sum \left(\beta_i * d_i\right) \tag{3-16}$$

where d_i is the percentage coverage of different land uses in the watershed

Coverage of different land cover types for the Upper Ruvu watershed were estimated and are shown in Chapter 1 as summarized in Table 3-3. The sensitivity of land use to streamflow was then calculated using equation 3-15. The value for sensitivity of land use was found to be 0.49 and sensitivity to evapotranspiration was found to be -0.23. These values were then used in equation 3-12 for calculating change in streamflow as influenced by climate (ΔQ_{clim}).

Table 3 - 3. The percentage coverage of different land uses in different time periods

Land Use	% Area in 1991	% Area in 2000	% Area in 2015	% Mean Area
Natural Forest	17.2	10.2	3.9	10.4
Shrubland	15.2	18.4	21.0	18.2
Croplands	14.0	20.9	29.4	21.4
Woodland	28.9	24.3	16.1	23.1
Grassland	11.8	15.2	20.2	15.7
Bareland	2.4	2.4	3.8	2.9
Wetland	8.9	7.3	4.4	6.9
Water	1.5	1.2	0.5	1.1
Clouds/Shadows	0.2	0.2	0.9	0.4

The aggregation was also used for the calculation of the α index based on the coverage of the land uses shown in Table 3-3.

The impacts of human activities on streamflow is assessed through the relationship

$$\Delta Q_o = \Delta Q_{clim} + \Delta Q_{hum} \tag{3-17}$$

where ΔQ_{hum} refers to the change in streamflow caused by human activities, ΔQ_{Clim} refers to the change in streamflow caused by climate, and ΔQ_o refers to the change in observed streamflow. By considering the change calculated using equation 3-12, and the long term change in the observed streamflow in the reference and the change periods, the effect of human activities were quantified using equation 3-17.

3.3 Results and Discussion

3.3.1 Rainfall, streamflow and suspended sediments in the experimental watersheds

In the study area, rainfall occurred throughout the year, with higher amounts recorded in the long and short rainy seasons. The long rainy season runs from March through May (MAM) and the short rainy season runs from October through December (OND). On average the MAM season contributed between 47 and 52% of the total annual rainfall. Other seasons January and February (JF) and June, July, August and September (JJAS) received an average of at least 50 mm per month of rainfall. The station in Tegetero recorded total annual rainfall depth of 2169 mm and 2423 mm for 2014 and 2015 respectively. Likewise, the station at Kinole recorded a total annual rainfall depth of 2247 mm and 1941 mm for 2014 and 2015 respectively. Total rainy days in Tegetero were 198 and 214 for 2014 and 2015, respectively, while Kinole received rainfall for 228 and 178 days for 2014 and 2015, respectively. Figure 3-2 shows the mean monthly rainfall for the two stations for 2014 and 2015. There was less variation in temperature in the two years of monitoring with a mean value of 21°C, minimum of 17°C and maximum of 25°C. June and July were the coldest months with a mean temperature of 19 °C, and the hottest month was January with a mean temperature of 24 °C.

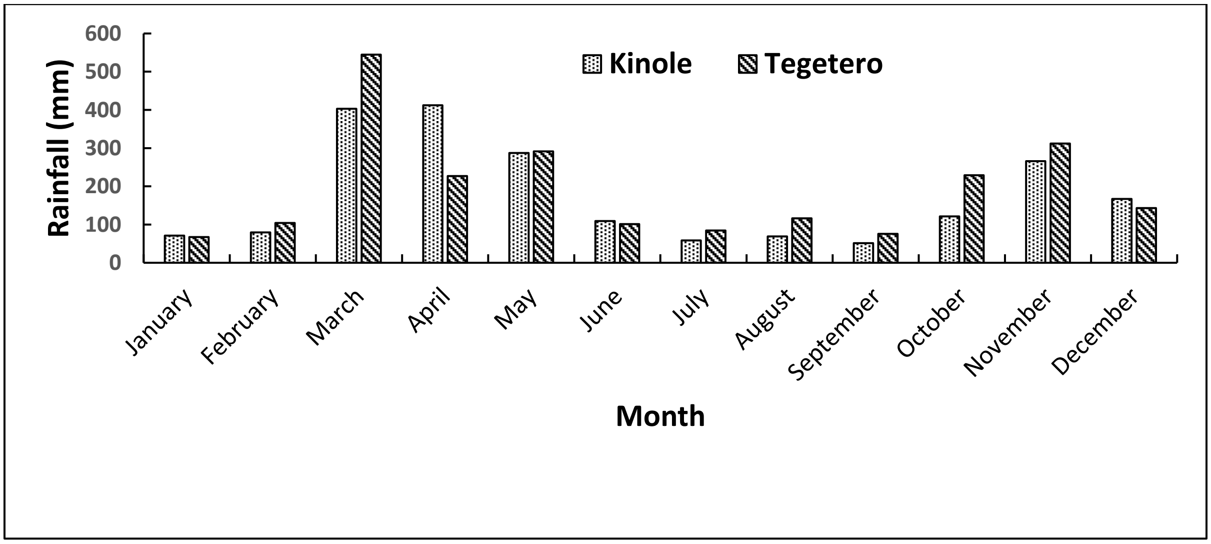


Figure 3 - 2. Monthly rainfall comparison for Tegetero and Kinole stations

3.3.2 Streamflow and water yield

Baseflow contribution was less from Kivumaga and Mkungazi than from Mbezi. Minimum values of 0.74 m^3/s and 0.23 m^3/s for 2014 and 2015 were observed at the Mbezi outlet with a mean value of 3.2 m^3/s. Minimum flow values of 0.1 m^3/s were observed at the Mkungazi and Kivumaga outlets and the mean discharges for the two years were 0.7 m^3/s and 1.1 m^3/s for the Mkungazi and Kivumaga outlets respectively. All the three streams are perennial with highest discharge recorded in April. In the two years of monitoring the maximum flows recorded at the Mbezi outlet was 21.7 m^3/s recorded on April, 12th, 2014, while maximum discharge values of up to 45 m^3/s and 52 m^3/s were observed at Mkungazi and Kivumaga outlets respectively. Figure 3-3 shows the streamflow response to rainfall in the Mbezi watershed and Figure 3-4 shows the streamflow response to rainfall in the Mkungazi watershed. It can be observed that there was an increase in streamflow following rainfall events, and this is consistent in all the three sub-watersheds. The high contribution of baseflow can be observed for the Mbezi sub-watershed (Figure 3-3) and less for the Mkungazi sub-watershed (Figure 3-4). A flashy response was evident in all the streams, and rise of streamflow could be observed immediately following rainfall events. In a study in western Australian Ruprecht and Schofield (1989) showed that streamflow increased in a watershed after forest clearing, due to the decrease in transpiration and interception loss. Using small watersheds in Kenya, Recha *et al.* (2012) compared streamflow and water yield from one forested watershed against three with different years after forest removal. It was found that streamflow did not respond rapidly to rainfall events, and a flashy response in the three watersheds with different land use history. It can be observed that there was a gradual increase in streamflow during the rainy season and baseflow was high during the dry season in the Mbezi watershed compared to Mkungazi. Due to the high coverage of forests (72% of the watershed area), it is expected that a part of the rainfall is intercepted by forests and part is taken as infiltration. In the watershed with high percentage of cropland (56%), a fast response of streamflow to rainfall during rainfall events and low baseflow during the dry season are expected.

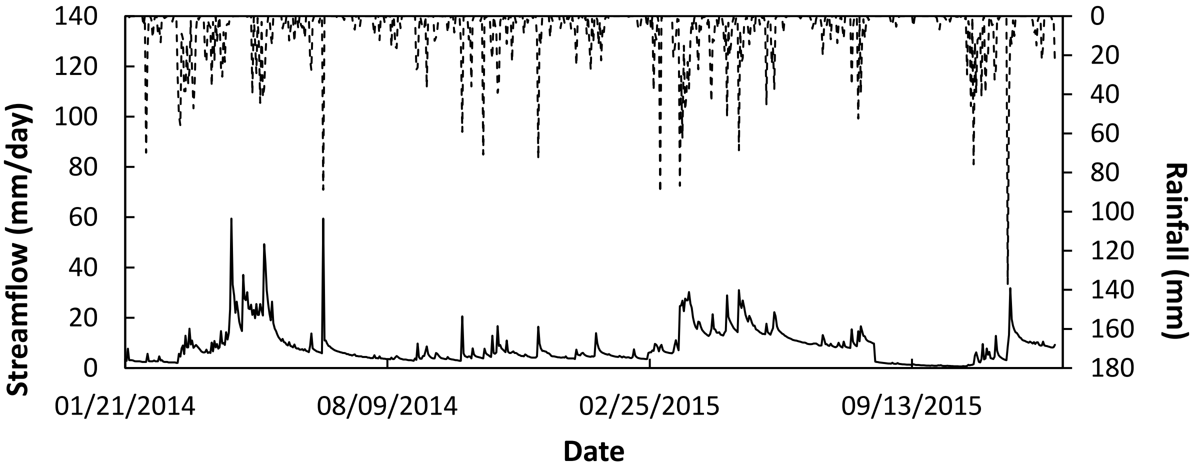


Figure 3 - 3. Daily Streamflow and rainfall of Mbezi sub-watershed

Average annual water yield of the three sub-watersheds for the two years of monitoring (normalized based on sub-watershed area Table 3-4) showed higher discharges in Mkungazi and Kivumaga compared to Mbezi. The ratio of total streamflow to total rainfall for the Mbezi sub-watershed was 0.59 while for Kivumaga and Mkungazi the RR was 0.77 and 0.91, respectively. In general changes in streamflow as a fraction of rainfall was higher in Mkungazi followed by Kivumaga and was less in Mbezi. The same pattern of changes was observed for DR in relation to rainfall as well as for BF in relation to rainfall. The Baseflow index was higher (0.76) for Mbezi sub-watershed and was the lowest (0.35) at the Mkungazi sub watershed outlet. This indicates that 60% of the rainfall that falls in the Mbezi watershed was transformed into stream runoff, while the percentages of rainfall that was transformed into runoff are higher in Mkungazi (91%) and Kivumaga (77%). The significant contribution of baseflow to total flow is shown by the BFI which is higher (0.76) for Mbezi sub-watershed and decreased following the levels of land disturbances for the other two sub-watersheds. Figure 3-5 shows the comparison of runoff (mm) from the three watersheds and it can be observed that hydrograph peaks were evident in the rainy season. Pronounced higher peaks can be observed in the long rainy season (March through May) than in the short rainy season. It can further be observed that higher peaks were found in Mkungazi compared to Kivumaga and Mbezi.

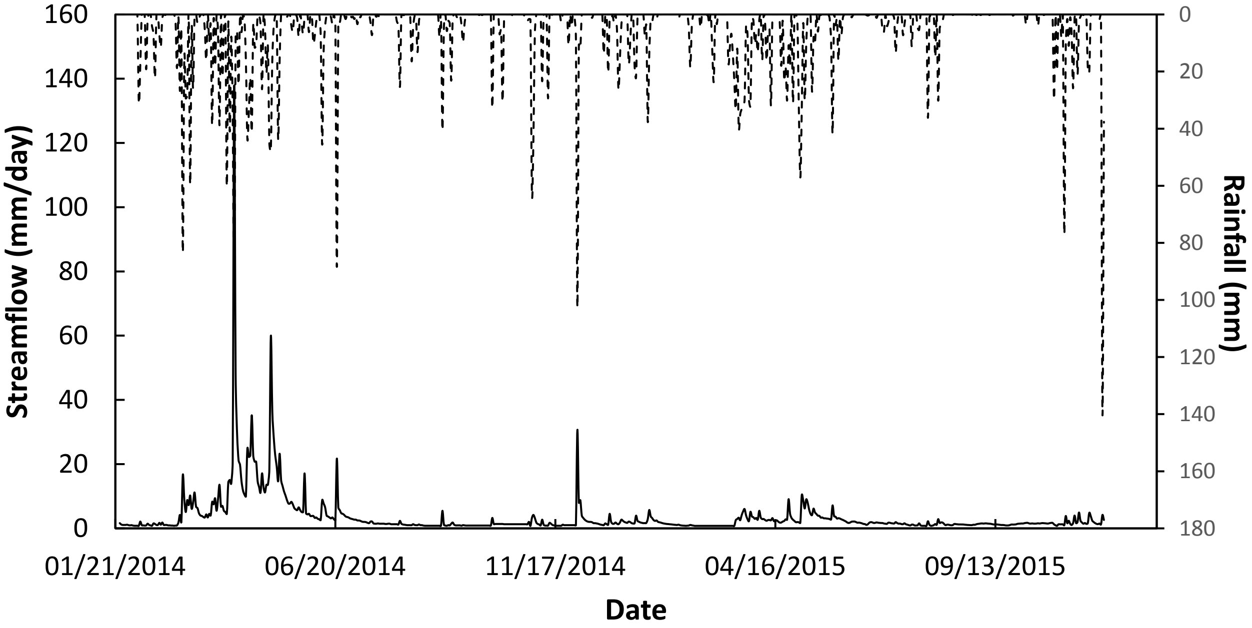


Figure 3 - 4. Stream flow for Mkungazi station

Figure 3-6 shows the cumulative flow duration curve for the three sub-watersheds. The flow duration curve shows that Mkungazi and Kivumaga had the same pattern for low-frequency flows (high flows) which were exceeded only about 23% of the time. However, under high-frequency flows (low frequency) Mbezi watershed was higher than the two watersheds. Nonetheless, the baseflow was higher in Mbezi compared to the two sub-watersheds. It is clear that the flow in the Mbezi sub-watershed is mostly dominated by baseflow, which is contributed by the presence of forest cover. The flow duration curve is consistent with direct runoff ratio and baseflow index in Table 3-4. Alterations of vegetation in a watershed can affect the distribution of daily flows or flow duration curve (Brown *et al.*, 2005). The knowledge that reduction in forest cover increases water yield is not new in hydrology (Brown *et al.*, 2005), but studies from paired watersheds have been inconclusive (Bosch and Hewlett, 1982). Results from a comparison of the three watersheds is in agreement with the knowledge that watersheds with a higher percentage of forested areas is likely to result in less water yield than cultivated and more disturbed watersheds.

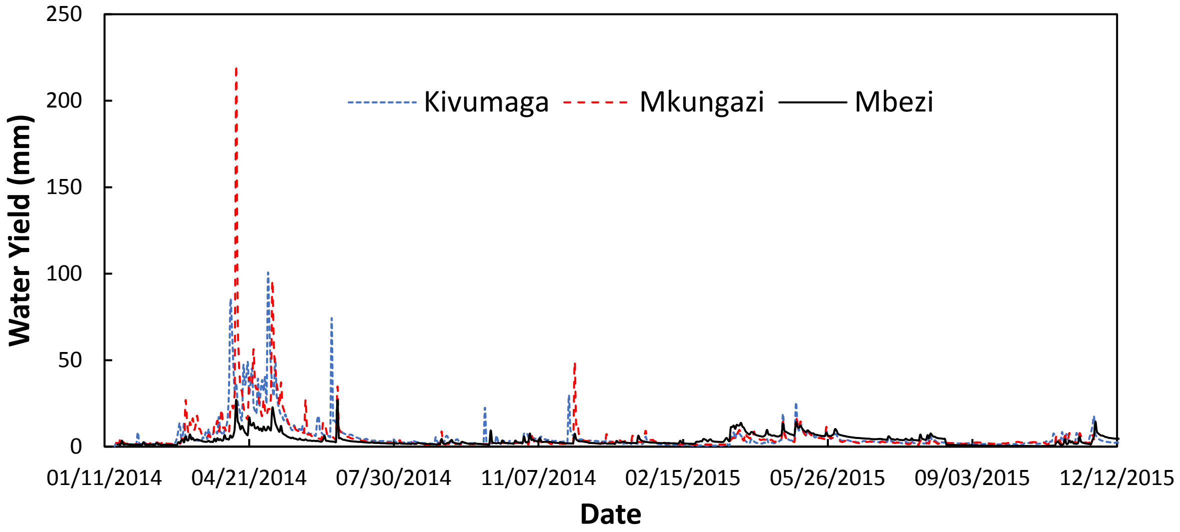


Figure 3 - 5.Water yield comparison for the three monitored watersheds

Table 3 - 4. Hydrological characteristics of the three stream tributaries

Parameter	Mbezi	Kivumaga	Mkungazi
Annual Rainfall(mm)	2296	2296	2094
Total Runoff (mm)	1365	1776	1917
DR (mm)	331	749	1231
DR_a	0.13	0.34	0.59
DF(mm)	1033.5	1027	686
BFI (-)	0.76	0.57	0.35
Flashiness Index(-)	0.18	0.47	0.43

[a] Direct Runoff/ Annual Rainfall

The flashiness index, which refers to the frequency and quickness of short term changes in streamflow follows oscillations in flow relative to total flow. The average flashiness index for the two years monitoring data was 0.18 for Mbezi sub-watershed, which was about 61% and 58% lower than the index at Kivumaga and Mkungazi sub-watersheds, respectively (Table 3-4). A high flashiness index indicates that the streams are flashier and the movement of water is rapid. According to Baker *et al.* (2004), land conversions may cause an increase or decrease in flashiness in the streams, and changes in land use and land management results in the increase of stream flashiness and decrease in baseflow. The fast response to rainfall for Mkungazi (Figure 3-4) and high flashiness index (Table 3-5) suggest that part of the rainfall produces quick flow moving rapidly to the stream channel. The high values of flashiness index computed for the watersheds with less forested areas happen to be consistent with the levels of disturbances. In the Mbezi watershed where 72% is covered by forests, a low flashiness index is calculated. In forest watersheds, combination of stable soil cover, roots and litter acts as a sponge soaking up water during rainy seasons, and releasing it more evenly during the dry season (Bruijnzeel, 2004), which corroborates our results (Table 3-5).

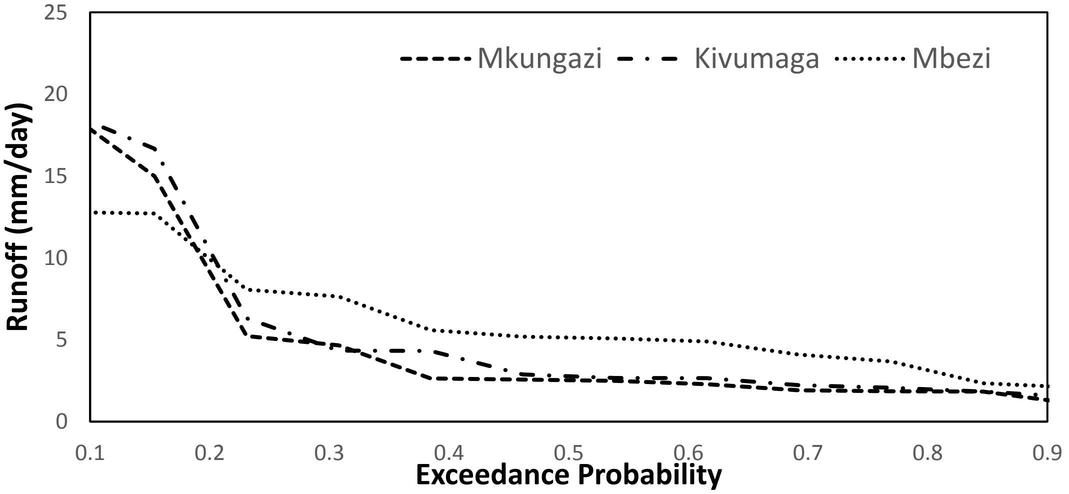


Figure 3 - 6. Flow duration curve for the three watersheds (mean values of 2014 and 2015)

3.3.3 Suspended sediments

Low values of suspended sediment concentration in the range of between 0.7 and 58 mgl^{-1}, with a mean value of 16.4 mgl^{-1} were recorded in the Mbezi watershed (Table 3-6). High values of sediment concentration ranging between 1 and 425 mgl^{-1} with a mean values of 94.3 mgl^{-1} were recorded for Mkungazi watershed, and between 2 and 242 mgl^{-1}, with a mean value of 63.2 mgl^{-1} were recorded in the Kivumaga watershed. The relationship between streamflow and suspended sediment concentration is shown in Figure 3-7. It can be observed from the figures that high values of sediment concentration were found in the rainy seasons. In the two years of monitoring, the long rainy season (March-May) produced more sediments than the short rainy season (October-December).

Annual sediment loads for Mkungazi reached 284.6 t km^{-2}yr^{-1}, almost double the estimates for Mbezi. Msaghaa *et al.* (2014) measured suspended sediments in the Ruvu river at Kibungo which is located downstream of our study watersheds and drains much larger area and calculated annual sediment loads of up to 450 t/km^2/year. The results suggest that human activities which are prevalent in the Mkungazi than in Mbezi and Kivumaga play a great role in the amount of sediment loads generated from the landscapes. In a study in Mexico, Duvert *et al.* (2010) reported annual sediment loads of up to 1500 tkm^{-2}yr^{-1} in three watersheds, with differences in loads attributed to differences in land disturbance.

We found a positive correlation between suspended sediment concentrations and flow, with correlations coefficients (r^2) of 0.23, 0.17, and 0.34 for Mkungazi, Kivumaga and Mbezi watersheds respectively (Figure 3-8). Scatter plots of suspended sediment concentration versus discharge are shown in Figure 3-8.

Table 3 - 5. Suspended Sediment values from the three watersheds.

Watershed	Mean SSC (mg/)	Mean Sediment load (t/day)	Wet season (t/day)	Dry season (t/day)	SSY (Annual) t/km^2/year
Mbezi	16.4	8.4	14.7	10.8	117.4
Kivumaga	63.2	12.1	35.2	3.2	230.1
Mkungazi	94.3	14.5	48.3	11.1	284.6

On average for the two years of sampling, daily sediment yield for Mbezi watershed was less by 50% from that of Kivumaga and 75% from that of Mkungazi watershed. The annual sediment yield for Mkungazi was 142% more than the Mbezi watershed, and about 23% more than that of the Kivumaga watershed. The wet season was responsible for much of the sediment yield (Table 3-5). The cropping pattern particularly of upland rice and maize (dominant crops) in the study watersheds usually follows the rainy seasons and starts in February when the land is tilled and planted and are usually harvested in June. In general the relation between hydrology and sediment patterns reveal that sediment concentration and sediment yield increase with land disturbances.

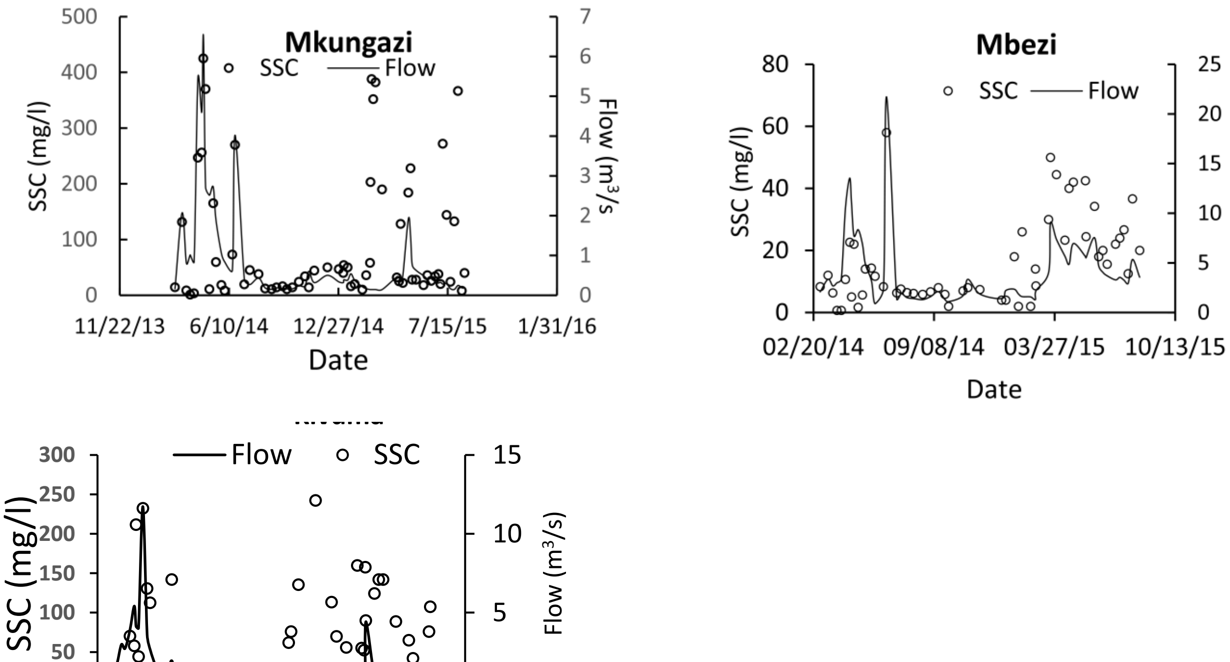


Figure 3 - 7. Suspended sediment concentration-Streamflow for Mkungazi and Mbezi watersheds

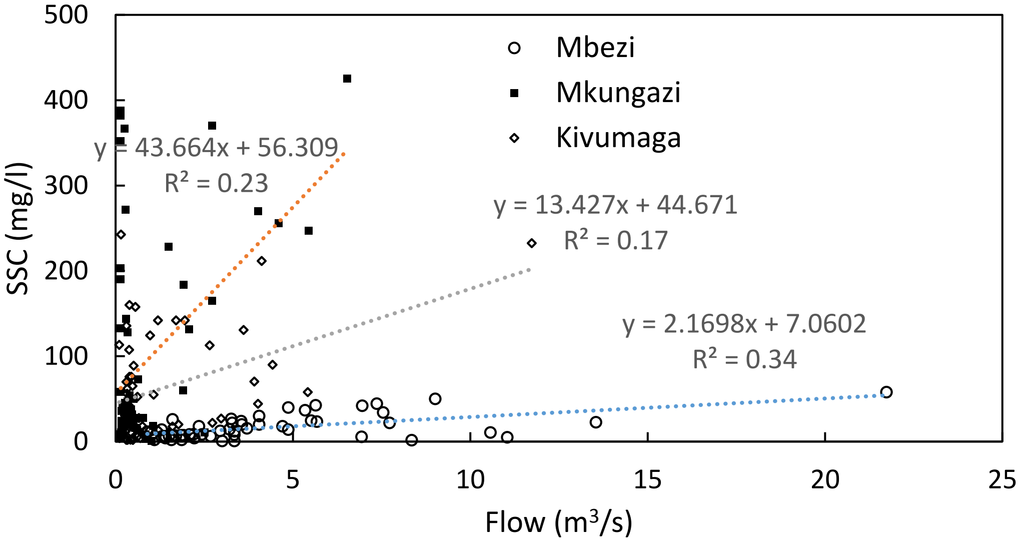


Figure 3 - 8. Scatter plot of sediment concentration and flow characteristics for the three watersheds

3.3.4 Analysis of climate variability and their impacts on streamflow at watershed scale

Long-term trend analysis and change point analysis of rainfall, ET_o and Streamflow

Trend analysis of annual rainfall data for stations in the watershed with data ranging from 1956 to 2014 were carried out using the Mann-Kendall non-parametric tests. Figure 3-9 shows the Mann-Kendall test statistics for the 11 stations within and around the watershed. The results show that out of the 11 stations, only three stations had an increasing trend, which was non-significant, and decreasing trends were observed from eight stations, with four of them being significant (Table 3-6).

The frequency of trends based on the four seasons shown in Table 3-6 and Figure 3-9 show that decreasing trends were dominant in all the seasons, with more significant decreasing trends found in the JF and JJAS seasons (both having 82% decreasing trends), with 64% and 46% statistically significant trends for JF and JJAS respectively. Of the two rainy seasons, the OND had 18% of the decreasing trends being statistically significant, while the MAM season had 36% of the decreasing trends being statistically significant.

Table 3 - 6. Rainfall trends for annual and different seasons for selected stations

	Station	Annual	JF	MAM	JJAS	OND
1	Moro WD	-0.7	-0.85	-0.17	-1.08	0.53
2	Mondo	-1.8+	-0.97	-1.10	-1.16	-0.89
3	Moro	-1.4	-0.95	0.52	-1.37	0.38
4	Morningside	-2.3*	-0.81	-2.07*	-2.91**	-0.92
5	Ruhungo	1.2	0.43	1.81+	0.15	0.73
6	Matombo	-4.0***	-2.55*	-3.1**	-2.24*	-2.54*
7	Kibungo	-0.85	-0.35	0.30	-0.91	-0.69
8	Mikula	1.7+	1.09	1.65+	1.94+	-0.85
9	Singiza	-3.23**	-1.76+	-3.74***	-1.99*	-0.38
10	Mlali	1.51	-3.39***	0.33	-2.25*	-0.80
11	Hobwe	-4.02***	-1.91+	-4.88***	-3.68***	-2.77**

*** Significant trend at 0.001 level of significance, ** significant trend at 0.01 level of significance, * significant trend at 0.05 level of significance, + Significant trend at 0.1 level of significance.

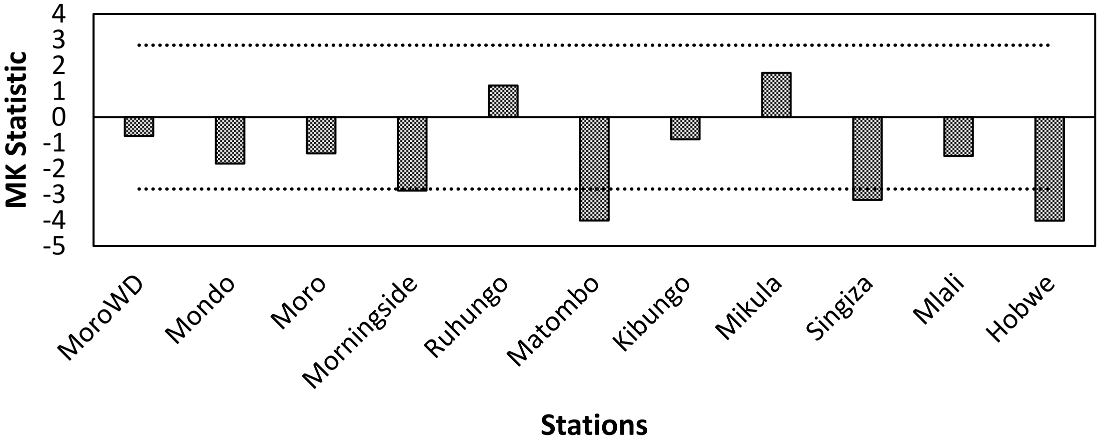


Figure 3 - 9.Results of the trend tests for the annual rainfall time series

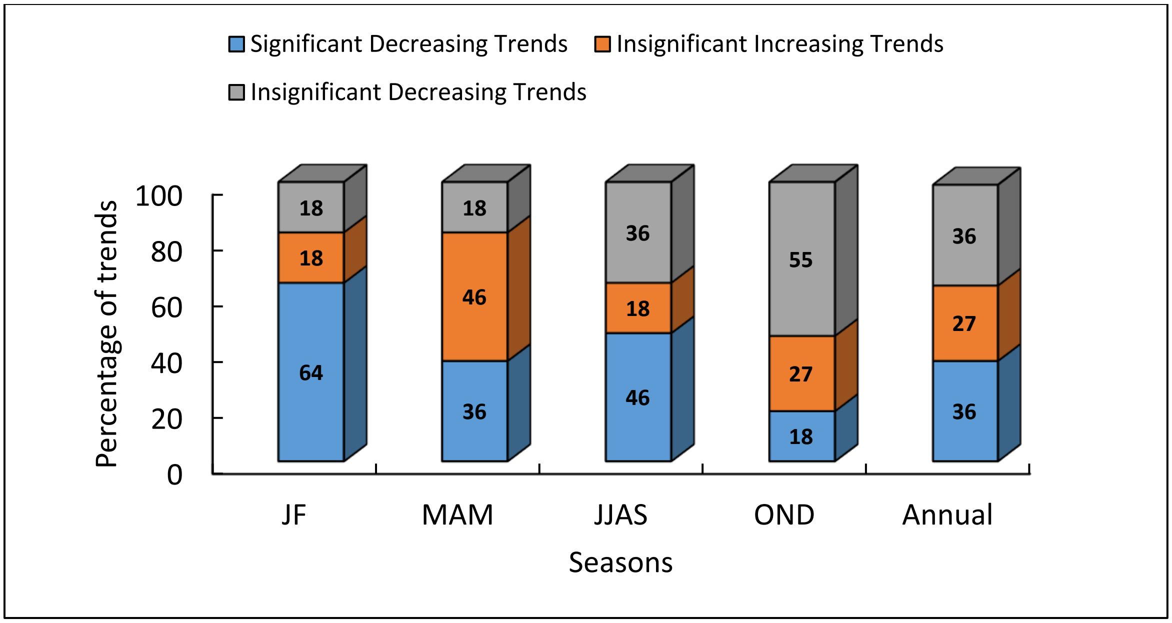


Figure 3 - 10. Frequency of rainfall trends for different seasons (JF: January-February; MAM: March-May; JJAS: June-September; OND: October –December)

The trend test was applied to the annual streamflow data over the period 1969 to 2012. The Z statistic of streamflow was -0.39, and showed a non-significant trend. Out of the four seasons in a year, only the January- February (dry season) showed an increasing trend with a Z-statistic of 0.6. The Z statistic for the other three seasons were -0.46, -1.22 and -0.07 for MAM, JJAS and OND respectively. It is clear that the dry season (which is the JJAS) had experienced more decreasing trends than the MAM and OND seasons.

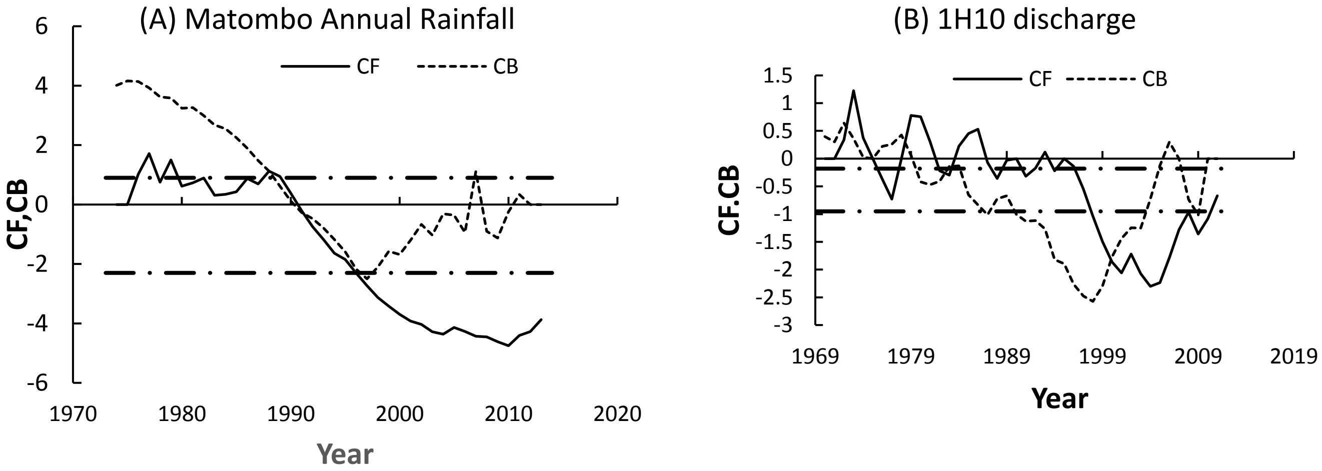


Figure 3 - 11. Change point detection in annual rainfall and discharge time in time series

Analysis of change point using the Mann-Kendall sequential test for the stations with significant trends in annual rainfall showed that a shift started in the mid-1980s but was evident at Matombo station in 1988 (Figure 3-11). Figure 3-11 shows the sequential Mann-Kendall change points for annual streamflow and annual rainfall, the abrupt change is noted at the intersection of the forward and backward time series. Abrupt changes in annual streamflow (Figure 3-11 (B) at 1H10 Ruvu at Mikula station started in the mid-1980s. Figure 3-12 shows the comparison of mean annual streamflows before and after the change.

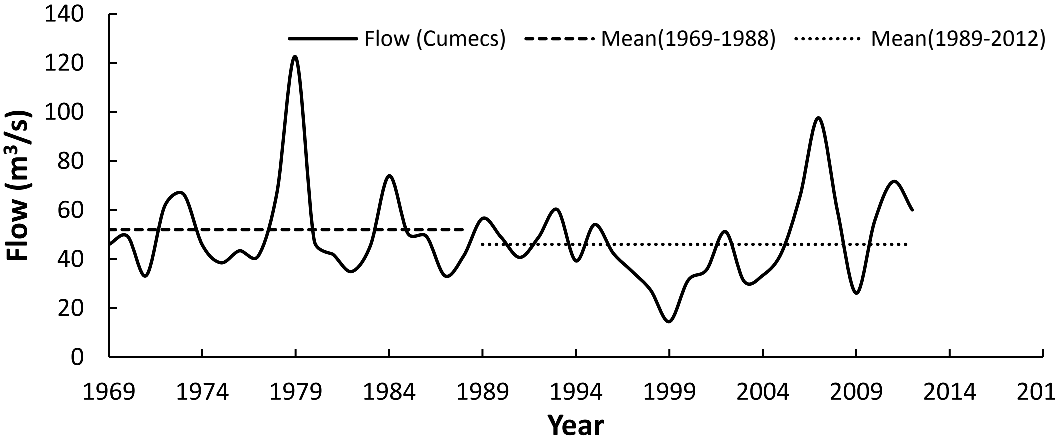


Figure 3 - 12. Changes of annual streamflow from 1966 to 2012 for 1H10 Ruvu at Mikula station

3.3.5 Changes in quantiles of extreme daily rainfall and streamflow in the watershed

Results from the quantile perturbation of daily time series of 10 stations in the watershed show variability in extreme values for different time periods. Figure 3-13 shows the MAM anomalies of extreme precipitation of two out of the 10 stations. Results show that the late-1970s to Mid-1980s were generally dry showing decreasing quantile perturbations. Increasing quantile perturbations were observed from the mid-1980s to the end of 1980s in 60% of the stations and were significant in 30% out of the 11 stations displaying a rather wet period. The highest significant change for the MAM season in 1990 was observed at Morogoro WD station with a change of 31% and the change of extreme precipitation from the mean for Matombo station was about 13%. An increasing trend of precipitation extremes that was significant in the early 2000s was visible in about 50% of the stations but was significant in 4 of the stations. A change of magnitude of up to 41% was observed at Mondo in 2001 and a change of about 58% was observed at Ruhungo station in 2002. However, the rest of the stations exhibited a decreasing trend that started in the 1990s up to the early 2000s and was significant at Matombo, Singiza and Mikula. The highest significant negative change of about 60% was observed at Matombo in 2002. Increasing anomalies for MAM season in the most recent years (2010s) were observed in Matombo, Morning Side and Kibungo. The rest of the stations showed decreasing anomalies of daily precipitation extremes for the MAM season in the most recent years (as can be seen from the Moro WD station in Figure 3-13).

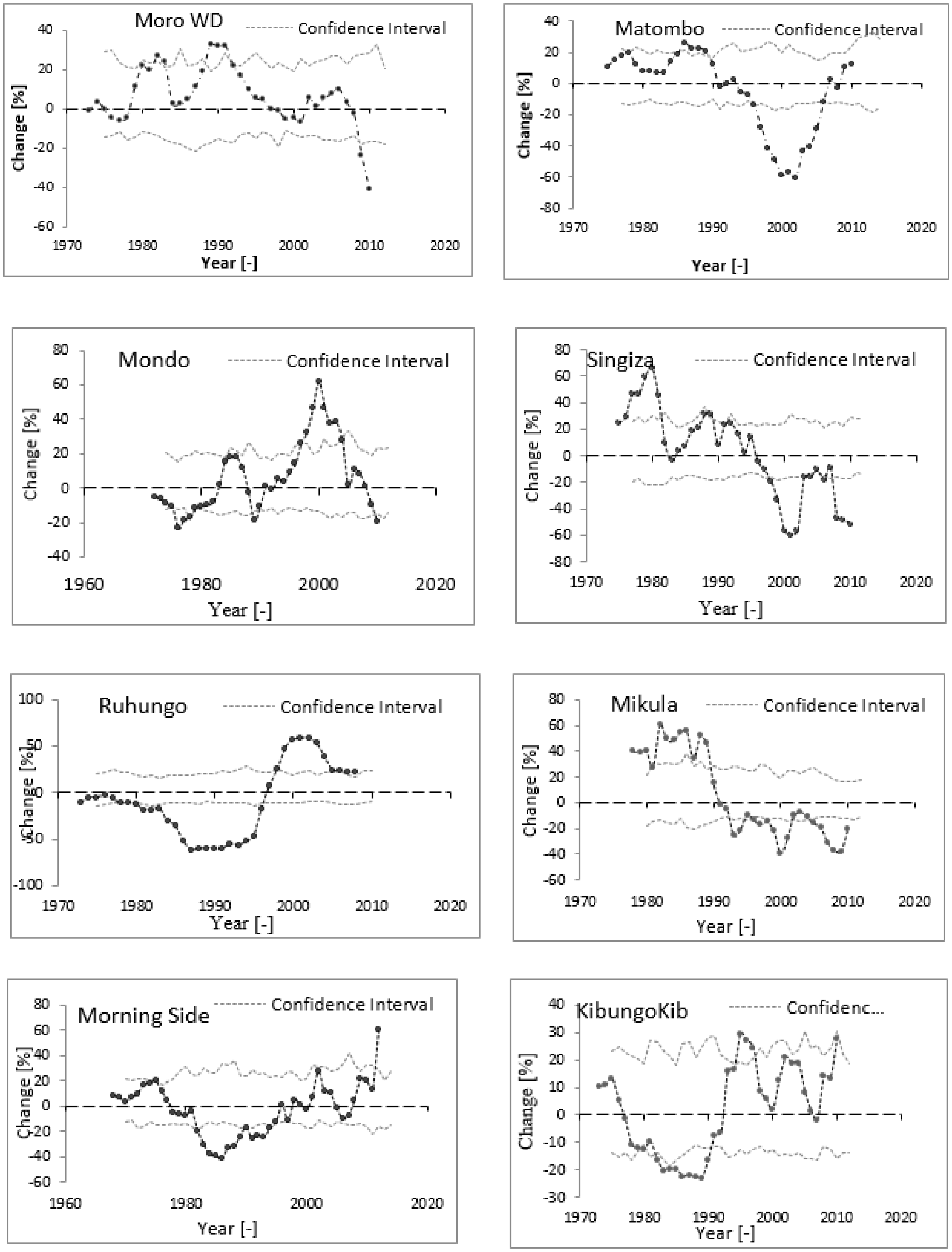


Figure 3 - 13. Quantile probabilities for two stations for MAM daily rainfall extremes (5-yr Block)

Changes in the extreme precipitation for the OND season show that the 1970s to early 1980s exhibited a dry to normal rainfall in about 50% of the stations. This was followed by increasing rainfall extremes from the mid-1980s to 1990s. A significant change of up to 228% from the reference was recorded at Hobwe station in 1994, 115% was recorded at Mikula station in 1986 and a change of about 42% in 1986 can be observed at Matombo station (Figure 3-13). A significant decreasing trend starting from the 1980s to the middle of the decade was observed for two stations (Ruhungo and Kibungo)

Unlike the MAM season where a positive change was significant around 1990 for most stations, the OND season exhibited negative changes that started around in the late 1980s to 2000s and were significant at Mikula (34% in 1997)), Ruhungo (18%), Kibungo (15% in 1989) and Matombo (68% in 2003). Increasing changes were observed from the 2000s but were significant only at Morningside (2000), Hobwe and Ruhungo (2005) reaching up to 53% from the reference mean. While almost all stations showed negative changes in extreme precipitation in the OND season in years after 2005, Ruhungo showed positive changes (up to 54% in 2008). The negative changes were significant at Mikula (46% in 2010), Hobwe (43% in 2010), and Morogoro WD (44% in 2010). Variability in extreme precipitation from the long term value was observed in all the years towards the present time.

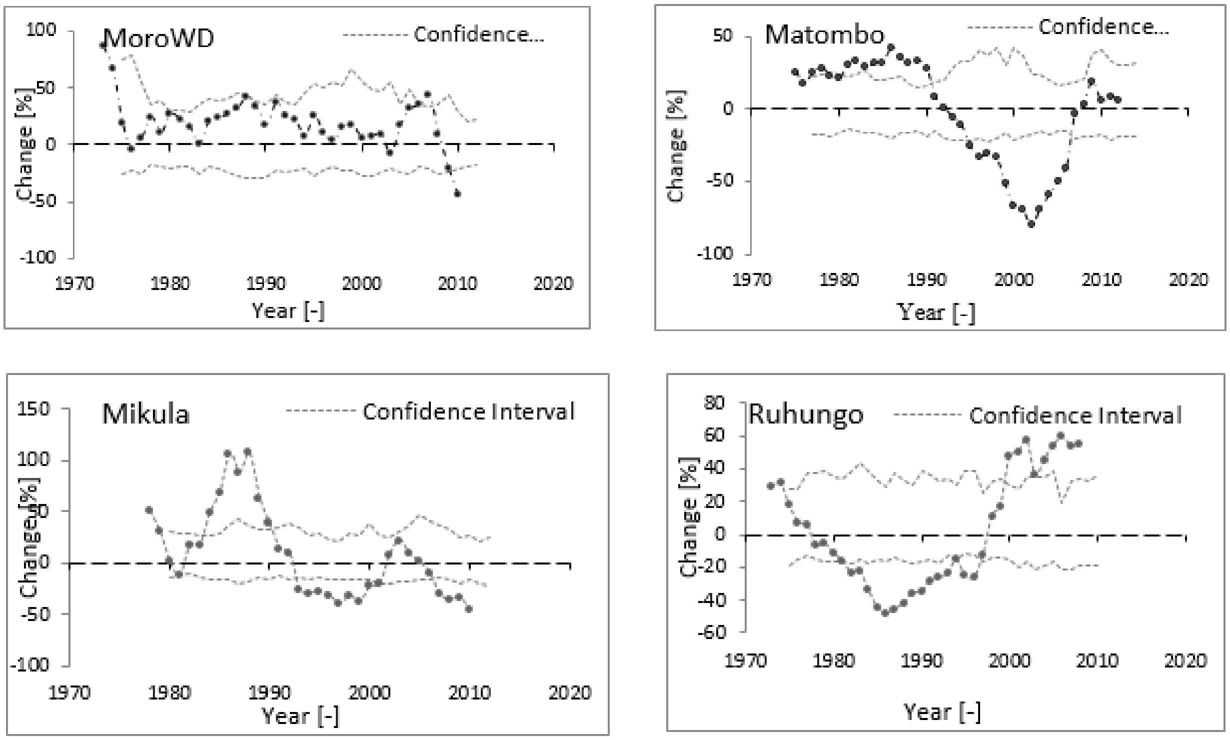


Figure 3 - 14. Quantile probabilities for two stations for OND daily rainfall extremes (5-year block)

Figure 3-15 shows anomalies for discharge at 1H10 Ruvu River at Mikula station during the long rainy season (MAM) and the short rainy season (OND). The MAM season was characterized by higher quantiles in the early 1970s (up to 40% change), and experienced decrease in the mid-1980s (up to 20% lower) and in the early 2000s and late 2010s. The OND season showed a somewhat similar pattern with significant extreme quantiles in the late 1970s, but a decrease started that became significant in 1983 (20% change from the long term mean) (Figure 3-14). A negative change started in the 1990s and became statistically significant from 1992 reaching 65% change in 2003. Thereafter a positive change in extreme values started up to the present time reaching 30% in 2008 (statistically significant from the mean).

Changes in the extreme precipitation for the OND season show that the 1970s to early 1980s exhibited a dry to normal rainfall in about 50% of the stations. This was followed by increasing rainfall extremes from the mid-1980s to 1990s. A significant decreasing trend starting from the 1980s to the middle of the decade was observed at Ruhungo (Figure 3-14)

Unlike the MAM season where a positive change was significant 1990 for most stations, the OND season exhibited negative changes that started in the late 1980s to 2000s and were significant at Mikula (a change of 34% in 1997), Ruhungo (18%), Kibungo (15% in 1989) and Matombo (68% in 2003). Increasing changes were observed from the 2000s but were significant only at Morningside (2000), Hobwe, and Ruhungo (2005) reaching up to 53% from the reference mean. While almost all stations showed negative changes in extreme precipitation in the OND season in years after 2005, Ruhungo showed positive changes (up to 54% in 2008). The negative changes were significant at Mikula (46% in 2010), Hobwe (43% in 2010), and Morogoro WD (44% in 2010).

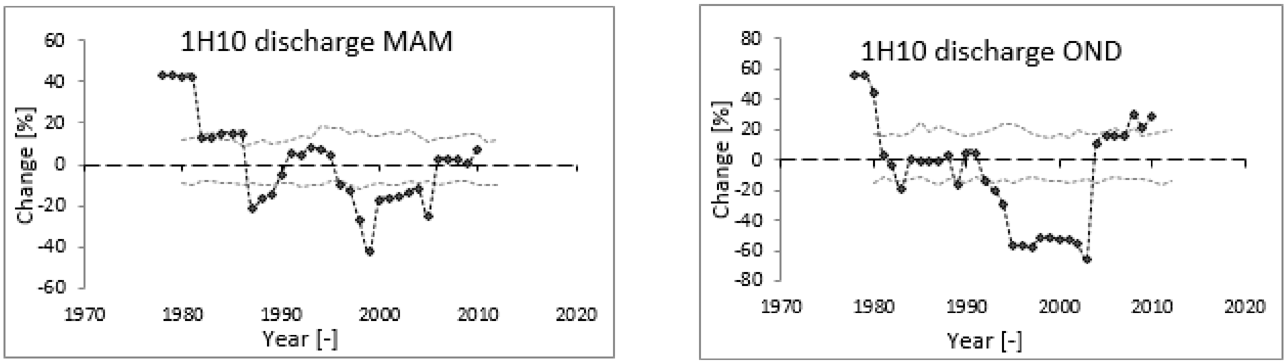


Figure 3 - 15. Anomalies in discharge quantiles at 1H10 Ruvu at Mikula for MAM and OND seasons.

Change in discharge quantiles for the two dry seasons, the January through February (JF) and June through September (JJAS) are shown in Figure 3-16. The results indicate that the watershed was dominated by negative quantiles and were significant in the 1980s, 2000s and 2010s for both the JF and the JJAS seasons. Significant positive quantiles of the extreme discharge values were visible in 1990 but a decreasing trend started from there on. It can be observed that the two seasons are dominated by decreasing or negative changes compared to the long term average.

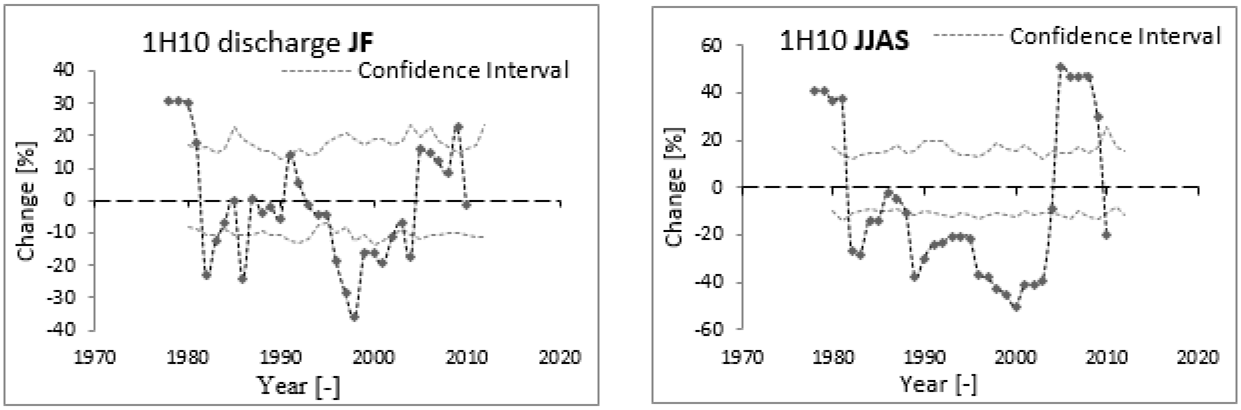


Figure 3 - 16. Change in discharge quantiles at 1H10 Ruvu at Mikula for MAM and OND seasons

3.3.6 Separation of the effects of climate variability and human activities on annual stream flow

The change in rainfall and potential evapotranspiration for the reference period (1966-1988 for rainfall, 1971-1988 for evapotranspiration) and the period that represents change (1989-2015) was calculated and results are shown in Table 3-7. Potential evapotranspiration was calculated using equation 3-1. Potential evapotranspiration in the separation of climate variability has also been applied by Wang *et al.* (2015) who calculated using the Hargreaves and Samani Equation (Hargreaves and Samani, 1985).

A double mass curve was used to confirm the time when human activity began to have influence on streamflow. A consistent relationship of cumulative precipitation-discharge (straight line) over time shows that there is no influence, but a consistent shift of the relationship may suggest that other factors apart from climate may have played a role on the change of streamflow (Yao *et al.*, 2012; Wang *et al.*, 2015). Figure 3-17 shows the double mass curves of rainfall-streamflow for the reference and change periods divided into the wet and dry seasons. The difference between cumulative observed seasonal streamflow and calculated values are referred to as change attributed to human activity disturbances. It can be observed (Figure 3-17) that, in 1988 there was a clear change of direction, which may suggest the influence of human activities on the streamflow. At annual scale, the differences in streamflow between the reference and the change period are shown in Table 3-7. The change point identified from the double mass curves is consistent with that found using the sequential Mann-Kendall test.

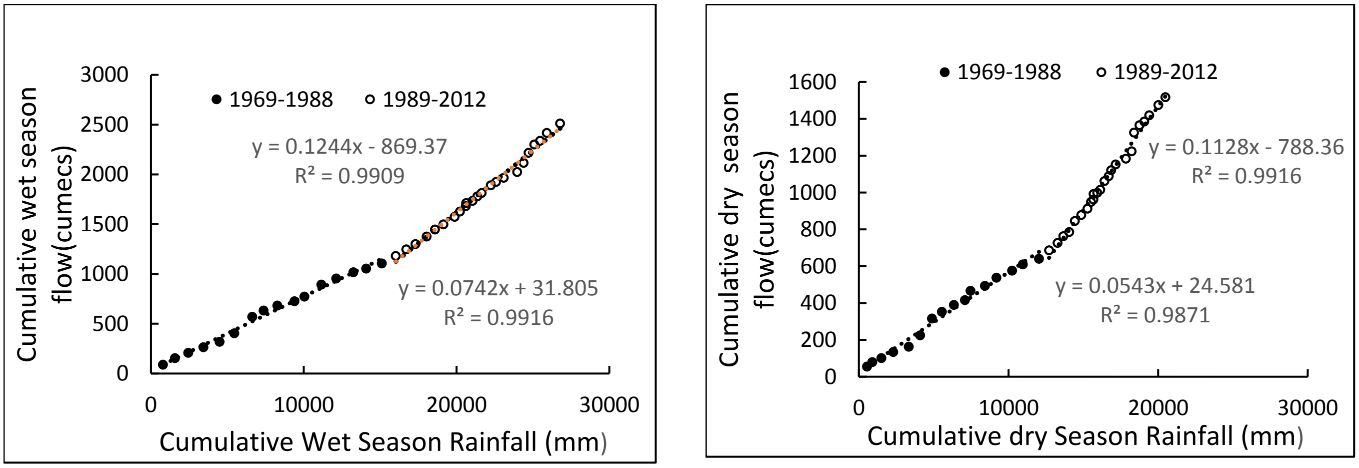


Figure 3 - 17. Double mass curve of seasonal precipitation and streamflow in the watershed

The change in rainfall and potential evapotranspiration in the two time periods are shown in Table 3-7. The results show that rainfall decreased by 4% and evapotranspiration increased by 2%. It can be realized that the change in rainfall and evapotranspiration is not significant for the years considered in this study.

Table 3 - 7. Changes in annual rainfall, potential evaporation and streamflow in the two time periods for both calculated and observed.

Time Period	Rainfall(mm)	ET_o(mm)
1959-1988	1345.8	1491.0
1989-2012	1291.2	1522.0
Change	54.7 (4%)	31 (2%)

The effects of the change in rainfall and evapotranspiration on streamflow were computed using equations 3-12 through 3-15. Based on the land use coverage in the study watershed and equations 3-13 and 3-14, the value of the sensitivity β and α were found to be 0.49 and -0.24 respectively. The sensitivity values to land use and potential evapotranspiration were used in equation 3-12 to calculate the change in streamflow as a result of climate variability (ΔQ_{clim}). The calculated change in streamflow due to climate was 19 mm. Using measured data from the outlet station a change in runoff from the baseline data was calculated. A change of 41.2 mm was found from the 293 mm of streamflow in the reference period (1969-1988) to 252 mm of streamflow following change (1989-2012), making a 14% decrease in annual stream flow (Figure 3-12). Using equation 3-16, the change attributed to human activities was computed from the known changes due to climate variability and the measured discharge at the outlet. Results show that the change in runoff as a result of human activities was 22.2 mm. The contribution of climate variability (19mm) and the contribution of human activities (22.2 mm) equal to the observed change (41.2 mm). Therefore, climate variability contributed 46% of the total changes in runoff, and human activities contributed 54% of the changes in runoff.

Changes of streamflow due to climate variability were mainly quantified by considering the changes the variability in rainfall and evapotranspiration. Quantification of the contribution of each driving factor to changes in streamflow is not only important for water resources planning, but also for sustainable water management and for identification of appropriate strategies, particularly for important watersheds like the Upper Ruvu watershed. Wei *et al.* (2013), showed the contribution of forest change and climate variability to changes in runoff, and concluded that for disturbed watersheds, contribution of human activities could be as important as that of climate variability.

In this study, we found that the contribution of human activities to changes of streamflow in the Upper Ruvu watershed was 54%, which was similar to the contribution of climate variability (46%). Although there are neither reservoir nor major water abstraction from the rivers in the uplands, but the increasing land use and land cover changes may contribute to the contribution of human activities to changes in streamflow.

It is important to note that there are uncertainties associated with the method used to separate the effects of human activities and climate variability on runoff associated with input data and model parameters. First, the hydrological sensitivity method requires long-term data of natural runoff without human activities. In this study data from two time periods (the baseline or before change period and the after change period) and the values signify mean values over the two periods, and ignore variability in the values within each period. Presence of some outliers in either period may affect the results. Second, accuracy may have been affected by the poor network of meteorological stations. Third, data for evapotranspiration were available from only one meteorological stations, and the method used to calculate evapotranspiration may have effects on the results. And finally, accuracy of the results may be affected by model parameters (Jiang *et al.*, 2011; Yao *et al.*, 2015).

3.4 Conclusions

Climate variability and changes in human activities have played a major role in the changes in the hydrology of the Upper Ruvu watershed from sub-watershed to watershed scale. Analyses of climate variables and suspended sediments from three sub-watersheds in Upper Ruvu show that the hydrology of the sub-watersheds was affected by variability in rainfall and human activities. As expected, increases in discharge during the rainy seasons were accompanied with increase in suspended sediments transported in the streams. However, during the dry season, flows were higher in the less disturbed Mbezi watershed compared to the more disturbed Mkungazi and Kivumaga reflecting the possible influence of anthropogenic activities, given that the three watersheds were did not have significance difference in topography, soils and rainfall amount. Anthropogenic activities in the three sub-watersheds were analyzed by comparing the levels of disturbances which was determined through the percentage of forest cover and croplands for a particular watershed. It was clear that the most disturbed watershed (Mkungazi) was associated with highest water yield and greatest sediment loads, while lower sediment loads were recorded in the Mbezi watershed.

Analyses of trends and change points show that the Upper Ruvu watershed is generally experiencing decreasing trends in annual and seasonal rainfall, which are significant in about 36% of the stations at annual time step, and range from 18% to 64% decreases for the stations in the four seasons. Changes in quantiles of daily rainfall and streamflow extremes displayed variability with positive and negative changes, showing that dry and wet periods have been interchanging, with the earlier years dominated by somewhat wetter periods compared to the most recent years.

Analyses of streamflow time series have shown the influence of climate variability and human activities. A decreasing trend in rainfall with a change point in 1988 was identified. The time series was divided into two periods, the reference (1956-1988) and the change period (1989-2014),. The computed changes indicate that climate variability contributed 46% and human activities contributed 54% of the change in streamflow. It is important to note that human activities especially land use and land cover changes are on the rise and their actual contribution may be much higher than the methods used in this study were able to quantify.

Acknowledgements

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References

Ahmed SA, Diffenbaugh NS, Hertel TW, Lobell DB, Ramankutty N, Rios AR, Rowhani P. 2011. Climate volatility and poverty vulnerability in Tanzania. Global Environmental Change, **21**: 46-55.

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, **300**: D05109.

Arndt C, Farmer W, Strzepek K, Thurlow J. 2012. Climate Change, Agriculture and Food Security in Tanzania. Review of Development Economics, **16**: 378-393. DOI: 10.1111/j.1467-9361.2012.00669.x.

Baker DB, Richards RP, Loftus TT, Kramer JW. 2004. A new flashiness index: Characteristics and applications to midwestern rivers and streams1. Wiley Online Library.

Baker JL. 2012. Climate change, disaster risk, and the urban poor: cities building resilience for a changing world. World Bank Publications.

Bloomfield J, Allen D, Griffiths K. 2009. Examining geological controls on baseflow index (BFI) using regression analysis: An illustration from the Thames Basin, UK. Journal of Hydrology, **373**: 164-176.

Bosch JM, Hewlett J. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of hydrology, **55**: 3-23.

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology, **310**: 28-61. DOI: http://dx.doi.org/10.1016/j.jhydrol.2004.12.010.

Bruijnzeel LA. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture, ecosystems & environment, **104**: 185-228.

Chen H, Guo S, Xu C-y, Singh VP. 2007. Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. Journal of hydrology, **344**: 171-184.

Conway D, Persechino A, Ardoin-Bardin S, Hamandawana H, Dieulin C, Mahe G. 2009. Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century. Journal of Hydrometeorology, **10**: 41-59. DOI: Doi 10.1175/2008jhm1004.1.

DAWASA. 2008. Environmental Impact Assessment Statement for Kidunda Dam, Executive Summary, Final, March 2008 Dar es Salaam: Prepared by Norconsult AS (Norway and Tanzania).

DeFries R, Eshleman KN. 2004. Land-use change and hydrologic processes: a major focus for the future. Hydrological Processes, **18**: 2183-2186. DOI: 10.1002/hyp.5584.

Diffenbaugh NS, Pal JS, Trapp RJ, Giorgi F. 2005. Fine-scale processes regulate the response of extreme events to global climate change. Proceedings of the National Academy of Sciences of the United States of America, **102**: 15774-15778.

Dooge J, Bruen M, Parmentier B. 1999. A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. Advances in Water Resources, **23**: 153-163.

Duvert C, Gratiot N, Evrard O, Navratil O, Némery J, Prat C, Esteves M. 2010. Drivers of erosion and suspended sediment transport in three headwater catchments of the Mexican Central Highlands. Geomorphology, **123**: 243-256. DOI: 10.1016/j.geomorph.2010.07.016.

Elliott AH, Oehler F, Schmidt J, Ekanayake JC. 2012. Sediment modelling with fine temporal and spatial resolution for a hilly catchment. Hydrological Processes, **26**: 3645-3660. DOI: 10.1002/hyp.8445.

Eshleman KN. 2013. Hydrological Consequences of Land Use Change: A Review of the State-of-Science. In: Ecosystems and Land Use Change, American Geophysical Union, pp: 13-29.

Fang N-F, Shi Z-H, Li L, Guo Z-L, Liu Q-J, Ai L. 2012. The effects of rainfall regimes and land use changes on runoff and soil loss in a small mountainous watershed. CATENA, **99**: 1-8. DOI: http://dx.doi.org/10.1016/j.catena.2012.07.004.

Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L. 2007. The shuttle radar topography mission. Rev Geophys, **45**.

García J, Gallego MC, Serrano A, Vaquero J. 2007. Trends in block-seasonal extreme rainfall over the Iberian Peninsula in the second half of the twentieth century. Journal of Climate, **20**: 113-130.

Hamed KH. 2008. Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis. Journal of Hydrology, **349**: 350-363. DOI: http://dx.doi.org/10.1016/j.jhydrol.2007.11.009.

Hargreaves G, Samani Z. 1985. Reference Crop Evapotranspiration from Temperature. Applied engineering in agriculture.

Hughes D, Jewitt G, Mahé G, Mazvimavi D, Stisen S. 2015. A review of aspects of hydrological sciences research in Africa over the past decade. Hydrological Sciences Journal, **60**: 1865-1879.

IPCC. 2007. The Physical Science Basin: Contribution of working group I tothe fourth assessment report of the Intergovernmental Panel on climate change. . Cambridge University Press.

IUCN. 2010. IUCN Eastern and Southern Africa Programme, 2010. The Ruvu Basin: A Situation Analysis., xvi + 96 pp. IUCN - ESARO Publications Service Unit

Jiang S, Ren L, Yong B, Singh VP, Yang X, Yuan F. 2011. Quantifying the effects of climate variability and human activities on runoff from the Laohahe basin in northern China using three different methods. Hydrological Processes, **25**: 2492-2505. DOI: 10.1002/hyp.8002.

JICA. 2012. The Study on Water Resources Management and Development in Wami/Ruvu Basin in the United Republic of Tanzania. Ministry of Water (MoW).

Kendall MG. 1975. Rank Correlation Methods. Charles Griffin.

Khoi DN, Suetsugi T. 2014. The responses of hydrological processes and sediment yield to land-use and climate change in the Be River Catchment, Vietnam. Hydrological Processes, **28**: 640-652. DOI: 10.1002/hyp.9620.

Kliment Z, Matoušková M. 2009. Runoff changes in the Šumava Mountains (Black Forest) and the Foothill Regions: extent of influence by human impact and climate change. Water Resour Manage, **23**: 1813-1834.

Koster RD, Suarez MJ. 1999. A simple framework for examining the interannual variability of land surface moisture fluxes. Journal of Climate, **12**: 1911-1917.

Li Z, Liu W-z, Zhang X-c, Zheng F-l. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. Journal of Hydrology, **377**: 35-42. DOI: http://dx.doi.org/10.1016/j.jhydrol.2009.08.007.

Lim KJ, Engel BA, Tang Z, Choi J, Kim KS, Muthukrishnan S, Tripathy D. 2005. Automated web gis based hydrograph analysis tool, WHAT1. Wiley Online Library.

Lim KJ, Park YS, Kim J, Shin Y-C, Kim NW, Kim SJ, Jeon J-H, Engel BA. 2010. Development of genetic algorithm-based optimization module in WHAT system for hydrograph analysis and model application. Comput Geosci-Uk, **36**: 936-944.

Liu Z, Yao Z, Huang H, Wu S, Liu G. 2014. Land Use and Climate Changes and their Impacts on Runoff in Yarlung Zangbo River Basin, China. Land Degradation & Development, **25**: 203-215. DOI: 10.1002/ldr.1159.

Longobardi A, Villani P. 2008. Baseflow index regionalization analysis in a mediterranean area and data scarcity context: Role of the catchment permeability index. Journal of Hydrology, **355**: 63-75.

Mann HB. 1945. Non-parametric test against trend. Econometrica, **13**: 245-259.

Mbungu W, Heatwole C. 2016. Modeling the hydrological responses to changes in land uses and land cover in the Upper Ruvu Watershed using SWAT and SWAT-VSA. Manuscript Chapter in a PhD Dissertation at Virginia Tech. June, 2016.

Mbungu W, Heatwole C. 2016a Land use and Land Cover changes and estimation of impacts on soil erosion potential in the Upper Ruvu Watershed, Tanzania: Integration of Remote Sensing, GIS and Modeling. Manuscript Chapter One as part of this dissertation - Under Review at Virginia Tech, June, 2016., Virginia Tech.

Mbungu W, Ntegeka V, Kahimba F, Taye M, Willems P. 2012. Temporal and spatial variations in hydro-climatic extremes in the Lake Victoria basin. Physics and Chemistry of the Earth, Parts A/B/C.

Milly P, Dunne K. 2002. Macroscale water fluxes 2. Water and energy supply control of their interannual variability. Water Resources Research, **38**: 24-21-24-29.

Milly PC, Dunne KA, Vecchia AV. 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature, **438**: 347-350.

Msaghaa JJ, Melesse AM, Ndomba PM. 2014. Modeling Sediment Dynamics: Effect of Land Use, Topography, and Land Management in the Wami-Ruvu Basin, Tanzania. In: Nile River Basin, Springer, pp: 165-192.

Mwandosya MJ, Nyenzi BS, Lubanga M. 1998. The assessment of vulnerability and adaptation to climate change impacts in Tanzania. Centre for Energy, Environment, Science and Technology.

Ngoye E, Machiwa JF. 2004. The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Physics and Chemistry of the Earth, Parts A/B/C, **29**: 1161-1166. DOI: http://dx.doi.org/10.1016/j.pce.2004.09.002.

Noel S. 2011. The Economics of Climate Change Tanzania Water Resources. Stockholm Environment Institute SEI-Africa Centre.

Ntegeka V, Willems P. 2008. Trends and multidecadal oscillations in rainfall extremes, based on a more than 100-year time series of 10 min rainfall intensities at Uccle, Belgium. Water Resources Research, **44**: W07402. DOI: 10.1029/2007WR006471.

Onyutha C, Willems P. 2015. Spatial and temporal variability of rainfall in the Nile Basin. Hydrology and Earth System Sciences, **19**: 2227-2246.

Raes D, Munoz G. 2009. The ETo Calculator. Reference Manual Version, **3**.

Recha JW, Lehmann J, Walter MT, Pell A, Verchot L, Johnson M. 2012. Stream discharge in tropical headwater catchments as a result of forest clearing and soil degradation. Earth Interactions, **16**: 1-18.

Ruprecht JK, Schofield NJ. 1989. Analysis of streamflow generation following deforestation in southwest Western Australia. Journal of Hydrology, **105**: 1-17. DOI: http://dx.doi.org/10.1016/0022-1694(89)90093-0.

Schwartz SS. 2007. Automated Algorithms for Heuristic Base-Flow Separation1. JAWRA Journal of the American Water Resources Association, **43**: 1583-1594.

Sen PK. 1968. Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc, **63**: 1379-1389.

Singh D, Tsiang M, Rajaratnam B, Diffenbaugh NS. 2014. Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. Nature Clim. Change, **4**: 456-461. DOI: 10.1038/nclimate2208 http://www.nature.com/nclimate/journal/v4/n6/abs/nclimate2208.html#supplementary-information.

Sneyers R. 1991. On the statistical analysis of series of observations. (No. 143).

Tabari H, Abghari H, Hosseinzadeh Talaee P. 2012. Temporal trends and spatial characteristics of drought and rainfall in arid and semiarid regions of Iran. Hydrological Processes, **26**: 3351-3361. DOI: 10.1002/hyp.8460.

Tabari H, Taye MT, Willems P. 2015. Statistical assessment of precipitation trends in the upper Blue Nile River basin. Stoch Env Res Risk A, **29**: 1751-1761.

Tekleab S, Mohamed Y, Uhlenbrook S, Wenninger J. 2014. Hydrologic responses to land cover change: the case of Jedeb mesoscale catchment, Abay/Upper Blue Nile basin, Ethiopia. Hydrological Processes, **28**: 5149-5161.

Tumbo S, Kahimba F, Mbilinyi B, Rwehumbiza F, Mahoo H, Mbungu W, Enfors E. 2012. Impact of projected climate change on agricultural production in semi-arid areas of Tanzania: A case of same district. African Crop Science Journal, **20**: 453-463.

Vogel RM, Fennessey NM. 1995. Flow Duration Curves .2. A Review of Applications in Water-Resources Planning. Water Resour Bull, **31**: 1029-1039.

Wang H, Chen L, Yu X. 2015. Distinguishing human and climate influences on streamflow changes in Luan River basin in China. Catena. DOI: 10.1016/j.catena.2015.02.013.

Wang J, Hong Y, Gourley J, Adhikari P, Li L, Su F. 2010. Quantitative assessment of climate change and human impacts on long-term hydrologic response: a case study in a sub-basin of the Yellow River, China. International Journal of Climatology, **30**: 2130-2137. DOI: 10.1002/joc.2023.

Wang W, Shao Q, Yang T, Peng S, Xing W, Sun F, Luo Y. 2013. Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. Hydrological Processes, **27**: 1158-1174. DOI: 10.1002/hyp.9299.

Wang WG, Shao QX, Yang T, Peng SZ, Xing WQ, Sun FC, Luo YF. 2013. Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. Hydrological Processes, **27**: 1158-1174. DOI: 10.1002/hyp.9299.

Wei XH, Liu WF, Zhou PC. 2013. Quantifying the Relative Contributions of Forest Change and Climatic Variability to Hydrology in Large Watersheds: A Critical Review of Research Methods. Water, **5**: 728-746. DOI: 10.3390/w5020728.

Willems P. 2013. Multidecadal oscillatory behaviour of rainfall extremes in Europe. Climatic Change, **120**: 931-944.

Yanda P, Munishi P. 2007. Hydrologic and Land Use/Cover Change Analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) Watersheds. For WWF/CARE Dar es Salaam, Tanzania.

Yao J-q, Zhao Q-d, Liu Z-h. 2015. Effect of climate variability and human activities on runoff in the Jinghe River Basin, Northwest China. Journal of Mountain Science, **12**: 358-367.

Yao Y, Cai T, Wei X, Zhang M, Ju C. 2012. Effect of forest recovery on summer streamflow in small forested watersheds, Northeastern China. Hydrological Processes, **26**: 1208-1214.

Yue S, Pilon P, Phinney B, Cavadias G. 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes, **16**: 1807-1829.

Zhang C, Zhang B, Li W, Liu M. 2014. Response of streamflow to climate change and human activity in Xitiaoxi river basin in China. Hydrological Processes, **28**: 43-50. DOI: 10.1002/hyp.9539.

Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research, **37**: 701-708. DOI: 10.1029/2000WR900325.

Zhang X, Zhang L, Zhao J, Rustomji P, Hairsine P. 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. Water Resources Research, **44**: W00A07. DOI: 10.1029/2007WR006711.

Chapter 4. Estimating Surface Runoff, Sediment yield and Curve Number using a Rainfall Simulator at Plot Scale in the Upper Ruvu watershed, Tanzania

Abstract

Deforestation, inappropriate farming practices, overgrazing and other human activities are major factors aggravating soil erosion and water quality degradation in the Upper Ruvu Watershed in Tanzania. The effect of biophysical and climatic characteristics on surface runoff and soil erosion is critical for resource managers and decision makers in creating awareness and in the design and implementation of strategies to combat the problem. This study was designed to quantify the impact of land use types and site characteristics on surface runoff and sediment generation, and estimate CN from three land use types in the upper Ruvu watershed, in Tanzania. The experiments were carried out using a portable rainfall simulator in 18 selected sites in three land use types (forest, grassland and cropland) with distinct variations on site characteristics (slope, ground cover, soil and moisture content). Rainfall simulations (75 mm h^{-1}) were conducted to generate 30 minutes of runoff on a 2 by 1.5 m runoff plot and runoff and soil loss was measured. Results indicate that higher mean surface runoff rates up to 48 mm h^{-1} were found within the cropland land use type compared to runoff rates of 24 mm h^{-1} for grasslands. The lowest runoff rates (6 mm h^{-1}) were found from forest land use. Similarly, mean soil loss was highest for cropland (94 gm^{-2}) compared to grassland (66 gm^{-2}) and forest (24 gm^{-2}). Correlation and regression analysis indicate that percentage slope, percentage ground cover and some soil properties had statistically significant effects on surface runoff and soil loss, and help to explain the variations in runoff and sediment yield across plots. Soil moisture affected runoff, with higher runoff generated from plots with wet versus dry initial conditions. However, higher soil losses were recorded from surfaces with dry initial conditions than from surfaces with wet initial conditions. Average CN values of 88, 57 and 80 were estimated for upland rice, forest and grassland, respectively.

Key words: Runoff, sediment yield, soil erosion, rainfall simulators, Curve Number, Uluguru

4.1 Introduction

Land conversions through anthropogenic activities and mismanagement of the natural landscape can cause enormous changes in the hydrological processes, resulting in reduced stream flow and water quality problems. Reduced vegetation cover as a result of human disturbances of the environment is one of the main causes of increased surface runoff, soil erosion and movement of nutrients downstream and a major contributor of non-point source (NPS) pollution (Novotny, 2003; Nunes *et al.*, 2011; Grismer, 2012; Kibet *et al.*, 2014). In addition, loss of soil fertility due to soil erosion by water poses serious problems affecting the productivity of agricultural lands (De Luis *et al.*, 2010; Ziadat and Taimeh, 2013).

Highlands in Tanzania, like the majority of East African highlands, suffer from severe soil erosion (Rapp *et al.*, 1972; Temple, 1972; Jones, 1996; Vrieling, 2006; Kimaro *et al.*, 2008; Msaghaa *et al.*, 2014; Nishigaki *et al.*, 2016) with impacts on agricultural productivity and food security (Defersha and Melesse, 2012), water quality degradation (Ngoye and Machiwa, 2004; Yanda and Munishi, 2007) and biodiversity loss (Burgess *et al.*, 2002). High soil erosion rates with values exceeding tolerable limits of about 10-12 t/ha/year (Milliman and Meade, 1983) have been reported in some parts of the Uluguru Mountains (Kimaro *et al.*, 2008). The alarming rates have largely been attributed to the increase in human activities, especially those related to expansion of croplands at the expense of forests and woodlands (Yanda and Munishi, 2007). The landscapes in the Uluguru Mountains are one of the most populated areas in Morogoro with a population density of about 300 persons/km^2 (URT, 2011) in some areas, almost four times the national average of 58/ km^2 for rural areas. Although agriculture is the major occupation, farming methods used are poor and farming in marginal areas and areas susceptible to soil erosion is commonly practiced. As part of this study as described in Chapter 2, we reported significant losses of natural forests and woodlands from 1991 to 2015 (77 % and 41% respectively), and an increase of agricultural lands from 14% in 1991 to 30% in 2015. Studies conducted in the area have highlighted the relationship between land use change and increases in runoff generation and soil erosion (Yanda and Munishi, 2007) and overall decrease in water quality (Ngoye and Machiwa, 2004; Yanda and Munishi, 2007; Msaghaa *et al.*, 2014). Soil erosion is not only responsible for water quality degradation, but also for depletion of the fertile top soil causing a decline in crop productivity. Loss of soil fertility is a major setback in the efforts to improve food security and household's income in the rural areas.

Planning for appropriate soil and land management techniques to reduce soil erosion requires an understanding of the relationships between factors contributing to runoff generation and soil losses. Various studies from a range of environments and landscapes have highlighted the interactions existing between surface and climate characteristics for runoff and erosional processes (Kosmas *et al.*, 1997; Srinivasan *et al.*, 2007; Nunes *et al.*, 2011; Peng and Wang, 2012; Zhao *et al.*, 2014). Land use or land cover, rainfall intensity, antecedent soil moisture content, and slope gradients are among the factors that influence the generation of runoff and soil erosion (Cerdà, 2000; Martínez-Murillo *et al.*, 2013; Ziadat and Taimeh, 2013; Zhao *et al.*, 2014).

However, studies on runoff and soil erosion problems in nature can be a difficult challenge because of the variability in rainfall characteristics (Moore *et al.*, 1983), soil characteristics, land use, cover and slope gradients and uncertainties governing the processes (Elhakeem and Papanicolaou, 2009). The use of plot-scale experiments and lumped-conceptual models have been helpful (e.g., McCuen, 2003; Beven, 2011; Eshleman, 2013) for analysis of impacts of changes in site characteristics on hydrological processes. Plot scale experiments are useful because of the ability to replicate measurements in both space and time and the ability to control environmental conditions to some extent (Eshleman, 2013). Due to their easy applicability even in remote areas, rainfall simulators have been used to study surface runoff and soil erosion (Walsh *et al.*, 1998; Humphry *et al.*, 2002; Srinivasan *et al.*, 2007; Grismer, 2012; Kibet *et al.*, 2014). Rainfall simulators allow for control of important variables (Bryan, 1981), expedite data collection processes and the possibility to study under controlled environment (Joshi and Tambe, 2010). They can be used to investigate different parameters such as impacts of land use practices, vegetation covers, slope, soil characteristics, best management practices, nutrients such as fertilizer on surface runoff and non-point source pollutants transport anywhere and at any time of the year (Dillaha *et al.*, 1988; Sharpley *et al.*, 2001; Arnaez *et al.*, 2007; Srinivasan *et al.*, 2007; Grismer, 2012). These studies are otherwise impossible under natural rainfall because of human disturbances and interference (Dillaha *et al.*, 1988; Boix-Fayos *et al.*, 2006).The use of lumped-conceptual models and physically distributed models has been considered useful (Beven and Binley, 1992; McCuen, 2003; Eshleman, 2013). Nonetheless, these models need to be calibrated using field measurements before they are used for local environments (Elhakeem and Papanicolaou, 2009). Rainfall simulators have been used to derive parameters used in hydrological, erosion and water quality models (e.g. Curve Number, USLE parameters, Erosion 3D parameters, WEPP parameters) (Wischmeier and Smith, 1978; Loch, 2000; Elhakeem and Papanicolaou, 2009; Schindewolf and Schmidt, 2012).

The SCS Curve Number is one of the widely used empirical model for predicting surface runoff from small watersheds (USDA, 1986). SCS CN method has been integrated in many other hydrological and erosional models such as the Soil Water Assessment Tool (SWAT) (Arnold *et al.*, 1998), USLE and its subsequent models such as RUSSLE (Wischmeier and Smith, 1978) water erosion prediction project (WEPP) (Flanagan *et al.*, 1995) and water quality models such as CREAMS (Knisel, 1980). Some of these models have been adopted for use in Tanzania, without proper modification due to lack of field data. The use of rainfall simulators is particularly important for Sub-Saharan African countries and data-scarce areas where long-term field monitoring under natural rainfall is often hampered by practical difficulties such as lack of funds, skills (Hughes *et al.*, 2015) and remoteness of the landscapes. Field experiments under simulated rainfall can be useful for provision of information unavailable from long-term monitoring experiments under natural condition. The objectives of this study were (i) to quantify the effect of land use, soil moisture condition and slope on surface runoff and sediment generation and ii) to estimated curve number from different land use types.

4.2 Materials and Methods

4.2.1 Description of the study area

The rainfall simulation experiments were carried out in the Kibungo sub-watershed in the Upper Ruvu watershed in Tanzania. The Upper Ruvu watershed flows from uplands in the Uluguru Mountains which are part of the Eastern Arc Mountains. The watershed lies approximately between latitudes 7° 00' and 7°11'23.5"S and longitudes 37°30' and 37°38'36.6"E, (Figure 4-1). The Upper Ruvu River Watershed covers an an area of approximately 7510 km^2. Major tributataries of the watershed are the Mgeta in the western part and Ruvu which comprises the Mvuha, Mmanga, Mfizigo and Mbezi located on the eastern part, meeting to form the main Ruvu river which discharges to the Indian Ocean (WRBWO, 2008). The Ruvu River is an important source of water supply for Dar Es Salaam city and coast region. Administratively, the watershed lies in the Morogoro Rural District in Morogoro region.

The mean annual rainfall in the watershed ranges from 700 mm to 2450 mm. The rainfall distribution pattern is bi-modal with the main rainy season from March to May (MAM), locally known as the *masika*, whereas the short rains usually start in October and end in December (OND) locally known as the *vuli*, which are mainly controlled by global circulation patterns. The bimodal pattern is usually associated with the northward and southward movement of the Intertropical Convergence Zone (ICTZ) and the El Nino-Southen Oscillation (ENSO) or other oceanic or atmospheric signals as well as the topography. Winds blowing from the Indian Ocean lose much of their moisture in the Uluguru Mountains in the form of orographic rain when they are forced to rise and undergo adiabatic cooling. The *La Nina winds* are responsible for drought in dry years. More rainfall is received in the high altitude areas than the foothills and lowlands. Lowlands immediately adjacent to these mountains have less precipitation. Temperature in the study area is variable with the mean monthly temperature ranging from 17.4° C (July) to 22.4° C (December).

The geology of the watershed can be grouped into Precambrian, Karoo, Jurassic, Cretaceous, Tertiary and Quaternary rocks. The occurrence of the precambrian is mainly in the Uluguru Mountains and can be divided into three major lithological groups: acid gneisses, granulites and crystalline limestone (IUCN, 2010; JICA, 2012). The Karoo rocks occurs in the southern area of the Uluguru Mountains consist mainly of sandstone and shale. Jurassic rocks occur in the eastern margin of the Uluguru Mountains.They consist of coarse sandstone, mudstone and oolitic limestone deposited in a marine environment. Cretaceous rocks, which lie on the elevated rolling hills, consist of clay, shale, calcerous sandstone, sandy limestone and mudstone. Sediments of Tertiary and Quaternary occur in the elevated rolling hills and along the Ruvu River flood plain. The Tertiary deposits consist of sandy clay, clayey sand with lenses of pure sand or clay, gravel and calcerous fragments. The Quaternary deposits were formed in an alluvial fan and are subject to swampy condition during the wet season; they consist of clay, silt, sand and rarely gravel (IUCN, 2010)

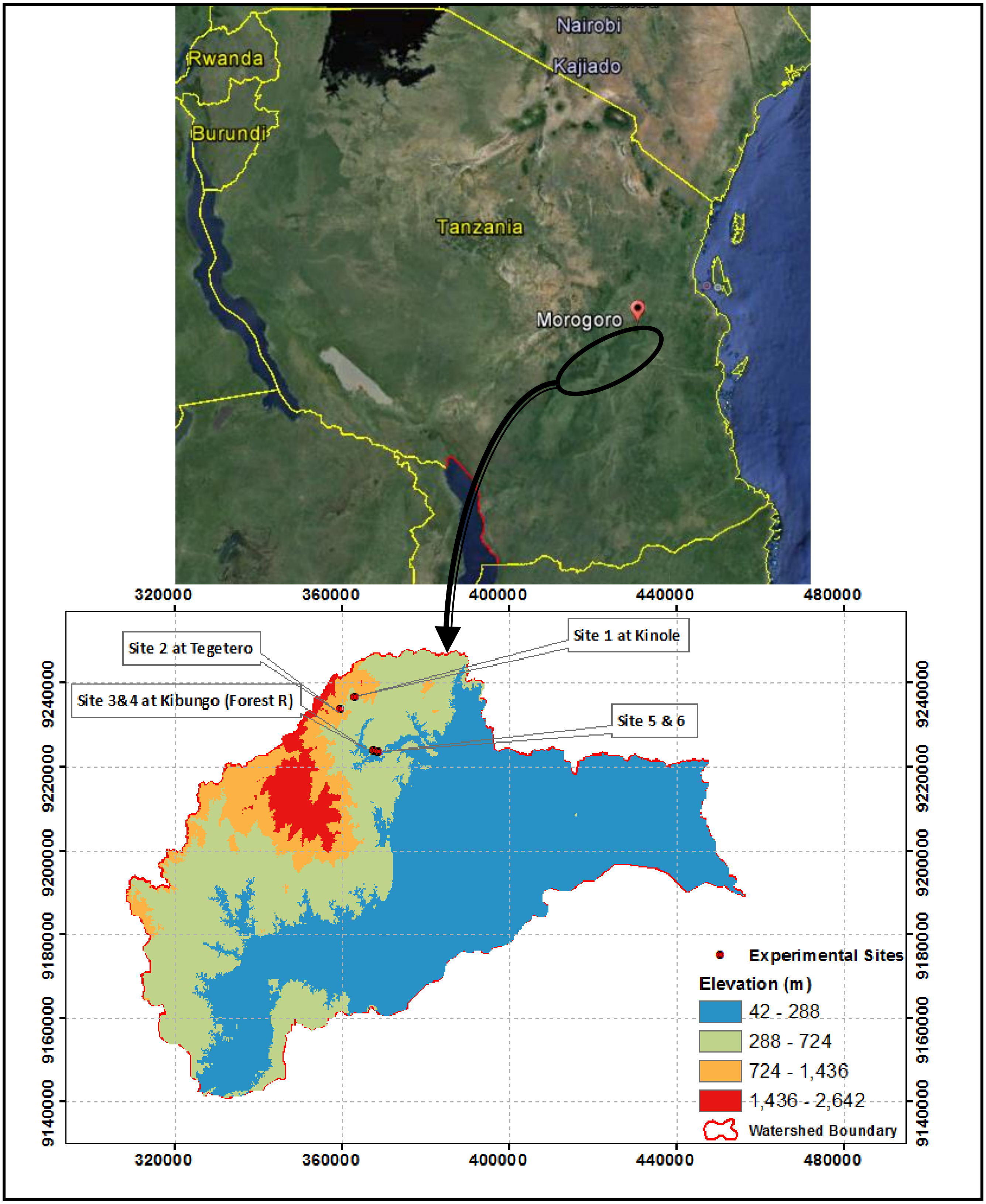

Figure 4 - 1. Location map of the study watershed and experimental sites

4.2.2 The rainfall simulator and experimental design

The portable rainfall simulator used for this study followed the design by Humphry *et al.* (2002) as improved from the National Phosphorus Runoff Project (NPRP) (Sharpley *et al.*, 1999; Sharpley *et al.*, 2001). Portability, less labor requirement, and minimum costs were important criteria considered in the design (Humphry *et al.*, 2002). The design for the simulator in this study considered among other factors terrain characteristics, plot size, accessibility to water sources and availability of materials in the locality. As our work was mainly based in remote areas, it was imperative that the simulator be portable, easy to use and require less power and labor to operate. All the components for the rainfall simulation experiment were designed to fit into a single full-sized pick-up truck.

A metal frame 3 m long, 2 m wide, and 3 meters high was used to surround a 2 x 1.5 m plot area. The frame provided a support for a single spray nozzle above the center of the plot area, and support for a wind screen around three sides of the plot during operation. The frames were constructed with steel connections that are easy to assemble and dismantle. Runoff plots 2m long and 1.5 m wide (Humphry et al., 2002) were bounded by steel plates driven at least 10 cm into the ground to isolate plot runoff. Runoff in the simulation plot was routed to a collection pan installed in the downslope edge of the plots. The collection pan was a triangular-shaped piece of galvanized steel sheet metals with edges molded to channel flow to an outlet. Following the protocol used in the NPRP simulation experiments, a constant rainfall intensity of 75 mmhr^{-1} was applied with the rainfall simulator to generate 30 min of continuous runoff from the 3 m^2 plots. Due to differences in initial conditions of different plot, the time from the rainfall initiation to when the runoff began was recorded for each simulation experiment.

To simulate rainfall with intensity that results in runoff and soil detachment, requires selecting an appropriate nozzle. (Hudson, 1961) reported a threshold of 30 mm h^{-1} for starting erosion under the tropical rain. Other studies (Okelo *et al.*, 2005; Joshi and Tambe, 2010; Zhao *et al.*, 2014) have used rainfall intensities greater than 60 mm h^{-1} for investigation of soil losses in tropical and semi-arid environments. Mutchler and Hermsmeier (1965) found that in order to attain high intensity, high discharge nozzles are required.

A coefficient of uniformity (Christiansen, 1942) was used to determine whether the rainfall was evenly distributed over the plot for each simulated rainfall event using the following equation:

$$CU = 1 - \frac{x}{y} \tag{4-1}$$

where CU is the coefficient of uniformity, x is the absolute deviation of rainfall depths from mean depth, and y is the mean rainfall depth. A single nozzle with 1/2GG 32Fulljet from Spraying Systems Co^{R} (www.spray.com) was used in this study. Water was supplied to the nozzle from a 200-liter water tank. The tank was continuously filled during the running of the experiment from a nearby water source. The water was pumped from the tank by a *Remco Aquajet ARC Pump* with a capacity of 5.3 GPM powered by N60 battery supplying 12 VDC which was continuously charged using a small power generator. Flow rate reaching the nozzle through the hose pipe was measured using an adjustable flow meter (Hydronix AFM-055-www.freshwatersystems.com). A sediment filter was connected in-line to prevent sediment from clogging the pump or nozzle. Runoff samples for sediment measurement were collected at 5-minute intervals from the time runoff started. To assess effect of initial soil conditions, two runs were carried out on each plot. The first run took place after a dry period, to represent dry initial conditions. The second run was carried out 30 minutes later after the end of the first run to represent wet conditions.

Experiments were conducted in three land use types which include croplands/upland rice, grasslands and forests in the Upper Ruvu watershed. For each land use type, two sites were selected for the simulation experiments to represent gentle and steep slopes. At each site, experiments were carried out on three plots (replicates) which were at least 100 m distance from each other, making a total of six simulations at each site.

Slopes in percentage and vegetation cover in percentage for each land cover were measured and recorded. Slope gradients of the plots varied from 9% to 35% and vegetation cover ranged from 30% to 95%. In general, cropland in the uplands are dominated by upland rice, maize, bananas, pineapples, and spices such as cinnamon and black peppers. While pineapple, banana and spices are almost perennial crops and do not involve land disturbances at a seasonal time scale, upland rice is the dominant crop especially in the long rainy season, practiced in the hillslopes with poor soil conservation practices. The experiments were therefore carried out in the upland rice, and were conducted after the crops had been harvested. For each of the three land cover types (forest, grassland and cropland), experiments were carried out for different plots, which exhibited different site characteristics in a factorial design. The surface characteristics examined for this study include slope steepness, initial moisture content, percentage cover and soil properties.

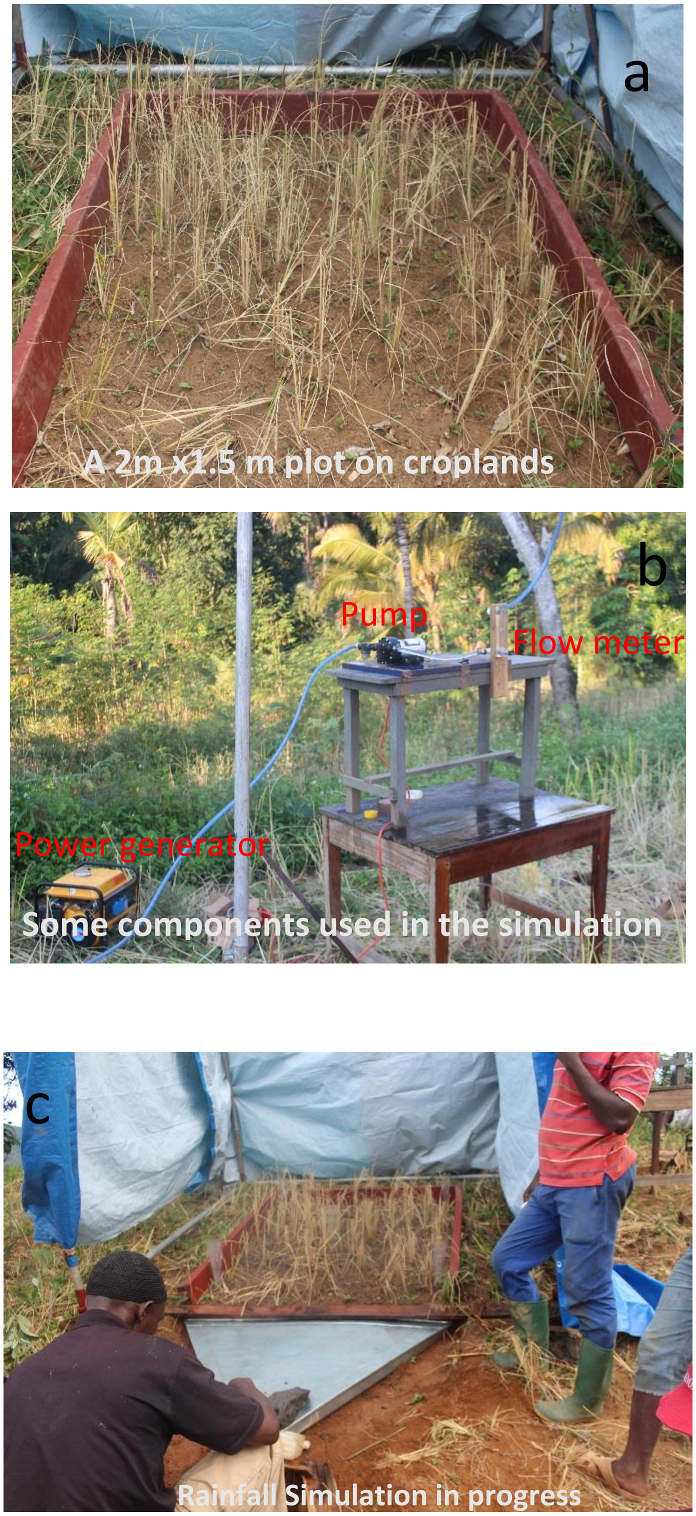

Figure 4 - 2. Simulation plot on croplands (a) some components used (b) simulation experiment in progress

4.2.3 Soil measurement and soil moisture measurement

A soil sample collected from 0-20 cm depth adjacent to each plot was used to determine textural composition (sand, silt and clay), pH, EC and soil organic carbon. Undisturbed soil samples were also taken from each plot for analysis of bulk density using the Eijkelkamp Soil Sampler. Representative soil moisture conditions were measured at three different places at the top, middle and bottom of each plot at a depth of 0 to 15 cm, using a theta probe (10HS Moisture Sensor. The moisture content values measured from the different places were averaged to obtain a single value before and after each run. The soil samples were analyzed in the laboratory using the Moberg (2001) laboratory manual. Soil organic carbon (OC) was measured using the dichromate oxidation method. The composite samples were analyzed for pH in water using pH meter in the laboratory, and soil particle size distribution was done using the hydrometer method. For each site, vegetation cover was visually estimated on five 0.25 m^2 quadrants distributed over the runoff plot.

4.2.4 Measurements and data analyses

The rainfall simulation studies were carried out during the dry season of 2015, between July, 14th and August, 15th, 2015. Daily rainfall recorded in Kinole area is shown in Figure 4-3. Simulator runs were preceded by two days without rain and it did not rain during the experiments. Experiments at Tegetero site were preceded by a 4-day dry period. The average soil moisture was about 21% for all the sites. We chose to use a constant rainfall intensity of 75 mm h^{-1} in order to take into effect the impact of moderate to high rainfall intensities. Hudson (1961) reported that erosion under the tropical rain starts at the threshold of 30 mm h^{-1}. And in order to take into effect the impact of moderate to high rainfall intensities we chose to use the 75 mm h^{-1} rainfall intensity. Since the aim was to compare runs over different land use/cover plots, the rainfall intensity was kept constant for all the replications. However, variability of rainfall intensity was observed ranging from 68 to 80 mm h^{-1}. The rainfall intensity for each experiment was calculated from the measured rainfall depth recorded for a known period of time. The rainfall depths were measured by five micro-rain gauges distributed in the borders of the plots.

Runoff rate was measured at 5-min intervals in a 5-L bucket. Sediment concentration was measured from runoff samples taken in a 1-liter bottle taken in 4 intervals within the runoff collection time. The time used to fill 1- liter bottle was recorded for each sample. Runoff volume was measured on-site using a cylinder and runoff samples for sediments were stored and transported to the laboratory. Analysis of sediment load in the water samples was carried out at the Soil Science Laboratory of Sokoine University of Agriculture in Tanzania. The water samples were filtered for suspended solids using a vacuum pressure fitted with a glass-fiber filter. The filters were first dried and weighed (in grams). The water samples were filtered, and the wet filters were dried in an oven at 105^{o}C for 1 h. The concentration of suspended solids was calculated using the equation:

$$\mathrm{TSS} = \frac{(\mathrm{A} - \mathrm{B}) * 1000}{\mathrm{C}} \quad (4\text{-}2)$$

where TSS = Total suspended solids (mg/l), A = weight of filter with dry residue (mg), B = dry weight of filter (mg) C = volume of sample filtered (ml)

Runoff and sediment yield amount and rate were determined using equations 4-3 and 4-4.

$$q_t = v*10/(a*t) \quad (4\text{-}3)$$

where q_t is the runoff rate (mm h^{-1}), v runoff volume in (ml), a - area of the plot (cm^2), and t-runoff time (h).

Sediment production rate (soil loss), also referred to as the soil loss is calculated as:

$$S_y = (s*10000)/ (a*t) \quad (4\text{-}4)$$

where S_y – sediment production rate (soil loss) ($g/m^2/h$), s-sediment yield (g).

Since the measurements were made at a plot scale, the environmental factors were assumed homogeneous for natural forests, croplands and grasslands. The temporal dynamics of soil moisture and its relationship with rainfall and vegetation pattern were analyzed.

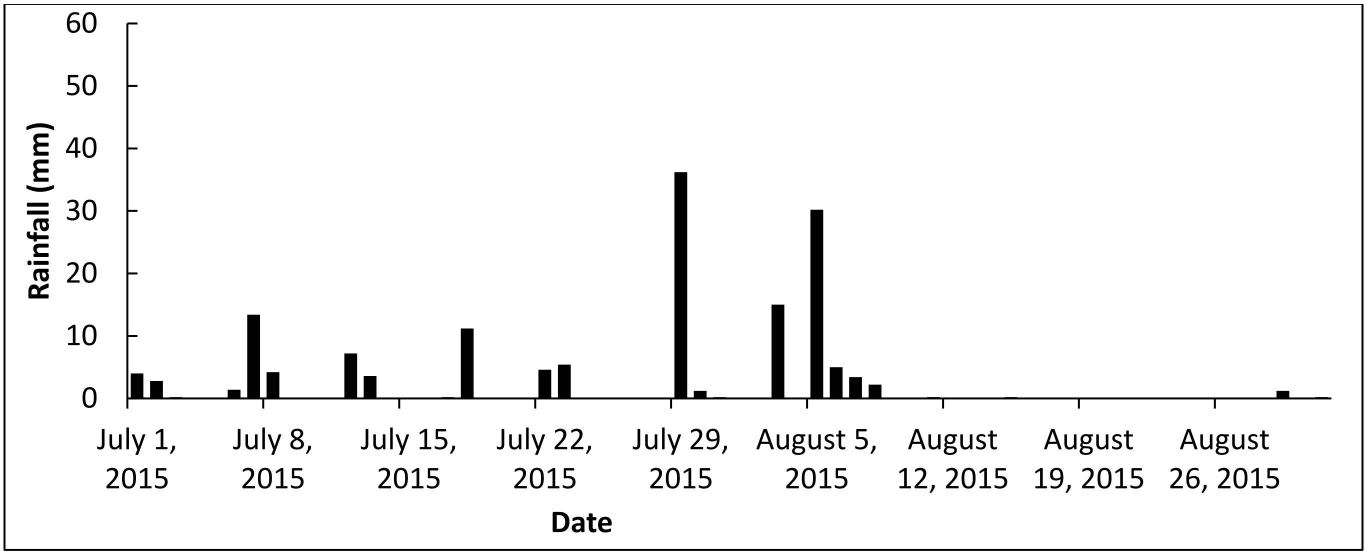

Figure 4 - 3. Daily rainfall depth distribution during the time of the experiments

4.2.5 SCS Curve Method and determination

The SCS-CN method was established for use on small agricultural watersheds, and has since been applied in a lot other environments including rural, forest and urban watersheds. The CN is a non-dimensional index that reflects the response of a specific soil under various site characteristics and management to a rainfall event through runoff and infiltration (USDA, 1986; Elhakeem and Papanicolaou, 2009). The CN represents the effects of land use, hydrologic soil group, hydrologic condition, antecedent moisture condition and varies from 0 (no runoff) to 100 (no infiltration). The method is based on the water balance equation and two fundamental hypotheses. The water balance equation is expressed mathematically as:

$$P = I_a + F + Q \tag{4-5}$$

The first hypothesis states that the ratio of direct runoff to potential maximum runoff is equal to the ratio of infiltration to potential maximum retention which is mathematically expressed as:

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{4-6}$$

And the second hypothesis states that the initial abstraction is proportional to the potential maximum retention.

$$I_a = \lambda S \tag{4-7}$$

where P is the total precipitation depth (mm), F is the cumulative infiltration after runoff begins (mm), Q is direct runoff (mm), S is the potential maximum retention (mm), I_a is the initial abstraction before runoff (mm), and λ is the initial abstraction (ratio) coefficient. I_a can be computed by accumulating the rainfall amount from the start of the experiment to the time of runoff and it consists of the amount that is taken to account for interception, infiltration and surface storage. The initial abstraction coefficient λ is frequently viewed as a regional parameter dependent on geologic and climatic factors (Bosznay, 1989; Mishra *et al.*, 2004; Mishra *et al.*, 2006; Mishra and Singh, 2013), which is assumed as 0.2 in the standard SCN-CN methodology. In a study by Woodward *et al.* (2003) using runoff and rainfall data from 307 watersheds or plots in the US found a better fit to the data with a λ value of 0.05. The initial abstraction coefficient of 0.05 has been found to have a better accuracy in other studies conducted in China (Fu *et al.*, 2011), in Ethiopia (Descheemaeker *et al.*, 2011) and in India (Gundalia and Dholakia, 2014). In this study, the value of λ=0.05 was used.

Using runoff plot derived from the rainfall simulator, CN for any given location with a specific soil and cover relationship can be determined from the range of rainfall depths with corresponding runoff depths by solving for S and I_a from the following equations;

$$Q = \frac{(P - I_a)^2}{P + S - I_a} \tag{4-8}$$

And

$$S = \frac{25400}{CN} - 254 \tag{4-9}$$

Using rainfall depths and runoff depths data from the rainfall simulation runs, the relationship between rainfall and runoff described in Eqn.1 was used to obtain the values of I_a and S by fitting non-linear regression equations using iterative non-linear least square fitting (e.g., Bates and Watts, 1988; Brown, 2001). Runoff and rainfall data from the six runs from three different adjacent plots at each site were plotted to obtain a 'best fit' using Eqn.8. The rainfall depths were recorded using a tipping bucket gauge located at the edge of the runoff plot and the runoff depths were recorded at 5-minute interval for each run. By using the relationship in Eqn.7, the value of S was calculated for each site. Further description of this approach can be found in Elhakeem and Papanicolaou (2009). Due to small number of samples statistical comparisons and influence of the different factors (soil moisture, slope, and vegetation cover) was not computed. There were two sites with a total of six runs for each land use type (upland rice, forest and grassland).

4.2.6 Statistical Analysis

Evaluation of the effects of surface characteristics and land use types on runoff and soil loss was carried out by descriptive statistics, correlation and regression analysis. The variables considered were the percentage ground cover, slope steepness, initial soil moisture content and soil properties. Statements of significance for the tests are based on 5% confidence level. Analyses were conducted using a combination of programs including R, MS Excel and JMP Software.

4.3 Results and Discussion

4.3.1 Site characteristics and soil properties

The site characteristics and soil properties of the experimental sites are shown in Table 4-1. The experimental plots located on croplands had an average slope of 24%, while the average slopes for forests and grasslands were 26%. Average percentage plant cover was the greatest in the experimental plots located in the forest lands (83%) mainly because it was covered with trees and leaves falling from the trees. The plant cover was lowest on the croplands (44%), while the grasslands had on average of 69% surface cover.

The soil characteristics of the sites show that in general the soils in the agricultural lands were dominantly clay to sandy clay, and those in the forest and grasslands were dominantly sandy loam to sandy clay loam. The croplands had a much higher clay percentage (50%) compared to 26% on forests and 31% on grasslands. Based on the pH values, the soils in the agricultural lands were more acidic with values ranging from 5.09 to 5.55 with an average of 5.30. The average pH value for the forest lands was 7.75 and for grasslands was 6.75. The average bulk density for samples collected from the three land uses did not show significant differences. The average soil organic carbon was higher for samples collected from forested lands (4.09) than those collected from agricultural lands (2.3) and grasslands (1.05) which help explain later the ability of forest soils to absorb water for infiltration than other soils.

Table 4 - 1. Site and soil characteristics of the experimental plots

Characteristics	**Cropland**		**Forest**		**Grassland**	
	Mean	S.D*	Mean	S.D*	Mean	S.D*
Slope (%)	23.9	9.8	25.8	6.28	25.7	5.68
Plant Cover (%)	44	14.8	83.3	9.85	69.2	14.22
Sand (%)	38.8	17.2	63.5	5.42	61.1	8.85
Clay (%)	49.6	12.8	26.0	4.27	30.7	8.14
Silt (%)	12.6	3.7	10.6	2.53	8.2	0.8
pH (%)	5.3	0.2	7.75	0.17	6.8	0.2
Electrical conductivity()	30.6	8.7	123.9	82.1	34.2	6.03
Bulk density (g/cm^3)	1.0	0.08	1.07	0.19	1.4	0.29
Organic Carbon (OC)	2.3	0.55	4.09	1.9	1.05	0.08
Texture	Clay->Sandy Clay		Sandy Clay Loam		Sandy Clay Loam	

S.D* = Standard Deviation

4.3.2 Runoff response to rainfall simulated from the land covers

Figure 4-3 shows results of runoff evolution during the simulation runs across all the plot for all land use types. Results show differences in runoff start time for the three land cover types. Runoff in croplands started about 1.2 minutes after the start of rainfall simulation. There was a delay for runoff start time in the grasslands and forests, where runoff started 1.8 and 2.2 minutes respectively. The differences in runoff start time within experiments across land cover types can be attributed to site factors such as cover type, cover percentage, soil properties and soil moisture content. The results show a sharp rise of runoff at the beginning of the runoff. Runoff levels out and becomes stable as a result of saturation, sealing and the reduction in capillary forces of the top soil. It can be observed from the results in Figure 4-3 that runoff was higher on croplands followed by grasslands and lowest response was recorded for experiments conducted in the forest land cover type. The runoff rate in the three land cover types; forest, grassland and croplands showed a logarithmic relationship with runoff start time (Table 4-2). Significant differences between mean runoff rates from all land cover types were observed. The mean runoff rate on cropland was about 48 mm h^{-1} which was higher than any other land use type at any time and for all initial conditions. Runoff rates on forests were significantly lower than those on grasslands and croplands for all initial conditions (Table 4-2 and Figure 4-3). The mean runoff rates for grasslands and forests were 25.8 and 6 mmh^{-1} respectively. Similarly, high runoff coefficients were found on croplands than on grasslands and forests (Table 4-3). A study by Okelo *et al.* (2005) in Njoro, Kenya using constant rainfall intensity reported a similar pattern, where more runoff was observed on grazing lands and agricultural lands than on indigenous forests and other types of forests.

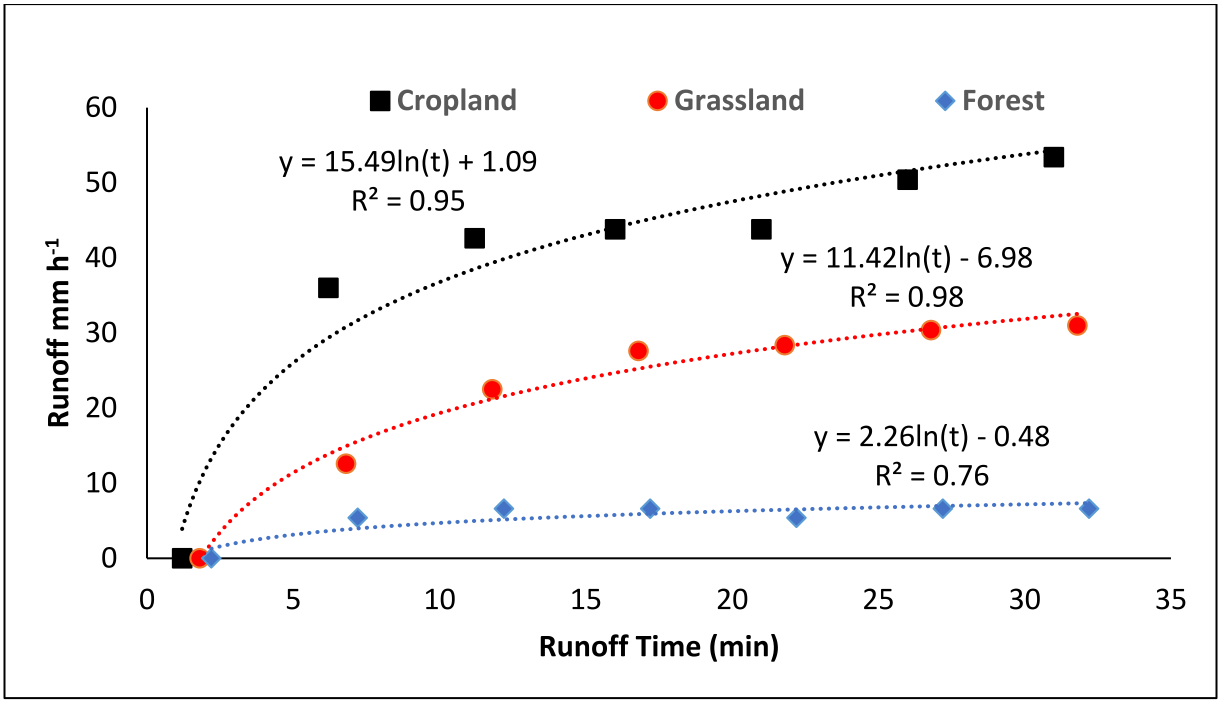

Figure 4 - 4. Runoff from simulations on different land cover types

Table 4 - 2. Correlation analysis between runoff rate (qt) and runoff start time (t) of the three land cover types

Land Cover	Regression Equation	Runoff Rate (mm h^{-1})	R^2
Forest	$q_t = 2.26 \ln(t) - 0.48$	6.0	0.76**
Grassland	$q_t = 11.42 \ln(t) – 6.98$	25.8	0.98**
Cropland	$q_t = 15.49 \ln(t) + 1.09$	45.0	0.95**

4.3.3 Influence of site characteristics on runoff rates for the three land cover types

Table 4-3 summarizes the effects of soil moisture, slope and percentage ground cover on runoff across all plots within the forest, grassland and cropland land uses types. Correlation coefficients in Table 4-3 show that percentage slope, percentage ground cover and soil moisture are important factors that influence runoff generation from field plots. It can be realized from the correlation and p values that slope had a positive influence on runoff rates, and runoff increased with increasing slope steepness for forests and croplands and was non-significant for grasslands.

However, the correlation between runoff rates and slope for the forest and cropland was only 0.35 and 0.2 respectively showing that slope is not the only site characteristic that is responsible for explaining variability in runoff rates from the three land cover types. The influence of slope for runoff generation was reported in other studies (Wischmeier and Smith, 1978; Joshi and Tambe, 2010; Ziadat and Taimeh, 2013). Joshi and Tambe (2010) reported subtle to noticeable changes of runoff among plots depending on slope steepness and surface characteristics on badlands in upper Pravara India. Sole´-Benet *et al.* (1997), found a positive correlation between runoff and slope gradient. Results (Table 4-3) show that plant/ground cover is negatively correlated with runoff rates for all land use types. The negative correlation confirm the fact that runoff rates decrease with increase in the percentage cover, and that a dense plant cover is an indication of little runoff intensity.

Table 4 - 3. Correlations and p values between runoff rates and site characteristics

Parameter	Forest	Grassland	Cropland
Slope	r = + 0.35, p = 0.0001	Non-significant	r = + 0.2, p = 0.0001
Ground Cover	r= - 0.37, p = 0.00011	r = -0.13, p= 0.0001	r = - 0.12, p = 0.0025
Soil Moisture	r = + 0.33, p = 0.0003	r= + 0.36, p= 0.0001	R = + 0. 54, p = 0.045
Mean Runoff (mm/min)	0.1	0.43	0.75
Runoff coefficient	0.07	0.28	0.50
R^2	0.49	0.43	0.48

Influence of soil moisture on runoff rate and runoff coefficient across all plots in all land use types was investigated and a positive correlation was found for all land use types. Table 4-3 shows the correlation was significant for all land use types. This explains the fact that under the same rainfall intensity, plots under wet initial conditions are expected to generate more runoff than those under initial dry conditions, due to the time needed to account for infiltration. Although, other surface characteristics play a role in runoff generation, it is accepted that saturated soils will generally result in increased runoff.

4.3.4 Influence of soil properties on soil erosion rates

The relationship between surface runoff and soil properties (soil texture, pH, Bulk density, Electrical conductivity and Organic carbon) was examined by correlation and regression analyses. Results indicate a strong correlation between soil properties and runoff rate. The regression coefficients between runoff and pH, bulk density, electrical conductivity, soil organic carbon and clay soil properties were R^2=0.66, R^2=0.76 and R^2=0.94 for forests, grasslands, and croplands respectively. However, no individual soil property revealed a strong correlation to runoff generation. Soil organic carbon and clay content had higher influence on runoff generation than other types of soil properties. Soil organic carbon was negatively correlated, suggesting that higher soil organic carbon resulted in less runoff, and vice-versa. Increased soil organic carbon in the soil has a tendency to increase its water holding capacity and conductivity, mainly because of its influence on soil aggregation and pore space distribution (Hudson, 1994; Saxton and Rawls, 2006). This can explain the fact that less runoff was observed from forests, as forests accumulate deposits of organic carbon from decaying plant materials and leaves that allow more infiltration. On the other hand, clay content also appears to influence runoff. Higher clay contents have more runoff, as clay tends to limit infiltration and hence increase runoff. The pH values were positively correlated to runoff rates, but only significant for runs from grasslands.

Table 4 - 4. Correlations and p values between runoff rate and soil properties

Parameter	Forest	Grassland	Cropland
pH(-)	Non-significant	r = 0.1, p = 0.0001	Non-significant
Bulk Density (g/cm^3)	r= - 0.13, p = 0.0001	Non-significant	r = - 0.36, p = 0.0025
Electrical conductivity	r = - 0.27, p = 0.033	Non-significant	r = -0.15, p = 0.012
Soil Organic Carbon (%)	r = - 0.26, p= 0.0001	r = - 0.1, p = 0.0001	r = - 0.36, p = 0.001
Clay (%)	r = + 0.05, p = 0.0493	r = + 0.1, p= 0.0001	r = + 0.41, p = 0.001
R^2	0.66	0.76	0.94

4.3.5 Soil erosion response to simulated rainfall from experiments in the three land use types

Table 4-5 shows the sediment outputs from experiments carried out in the three land use types. The mean sediment concentration was 1.45 g/l for forests, 4.5 g/l for grasslands and 5.7 g/l for croplands across all plots. Soil losses were higher for plots within the croplands than from grasslands and forests (Table 4-5). Higher mean soil loss of 94 g/m^2 was observed within croplands, compared to 65 g/m^2 within grasslands and 24 g/m^2 found within forests. Maximum soil loss values in the croplands were as high as 306 g/m^2 while the low values were about 8 g/m^2, showing high variability which is also indicated by the high standard deviation. Mean soil loss for grasslands and forests were 66 g/m^2 and 24 g/m^2 respectively.

Table 4 - 5. Sediment yields from rainfall simulations

Parameter	Forest		Grassland		Cropland		P-value
	Mean	Std	Mean	Std	Mean	Std	
Sediment Concentration(g/L)	1.2	0.9	3.7	1.7	6.2	4.4	<0.0001
Soil loss rate (g/m^2)	23.9	18.8	65.9	33.9	94.25	76.88	<0.0001

Figure 4-5 shows the erosion response to simulated rainfall across plots under all initial conditions. It can be observed that erosion rates were high at the beginning, and continued to decrease with time. Arnaez *et al.* (2007), reported high sediment concentration at the beginning of the experiments and the sediment concentration decreased with time. The evolution can be explained by high sediment availability at the beginning of the experiment and declining amount of sediment output over time, due to exhaustion of particles. Higher sediment concentration was recorded from croplands and variability within land use types decreased towards the end of the simulation period. Unlike runoff rates, which tends to remain stable after a sharp rise at the beginning, sediment concentration tends to decrease with time. As observed from Table 4-5 and

Figure 4-5 that sediment concentration was the highest in cropland/upland rice and was the lowest in the forest. This is attributed to the presence of debris, twigs and litter within the forest land use type that reduced soil detachment by rain splash erosion. Other researchers (e.g., Hewlett, 1982; Hartanto *et al.*, 2003) reported the influence of surface roughness on the reduction of soil erosion by water.

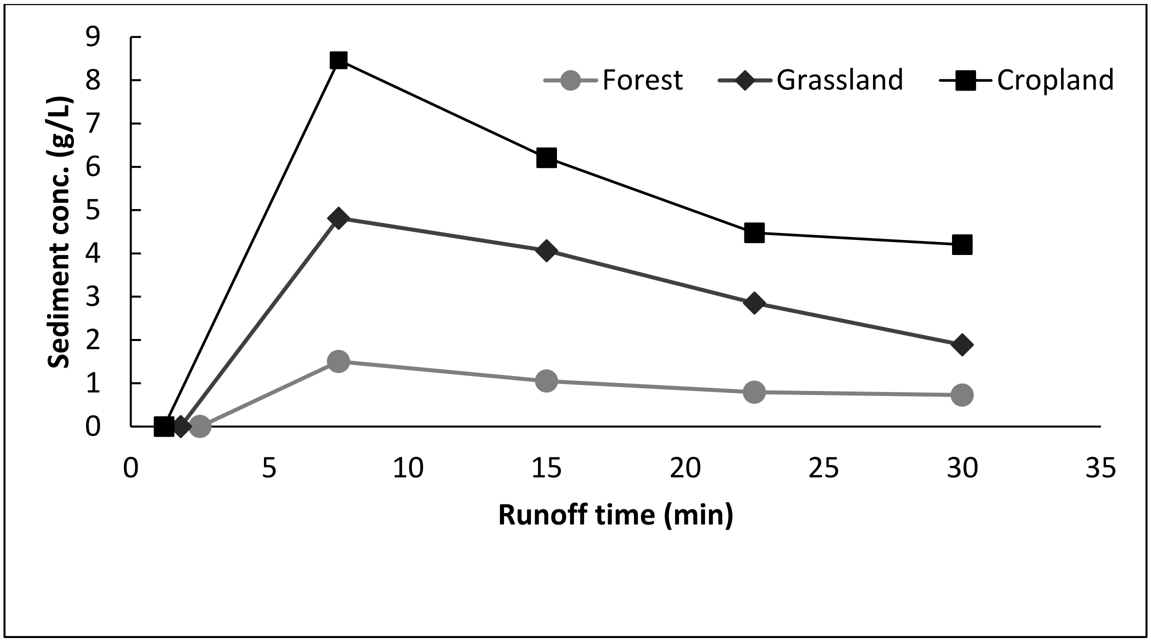

Figure 4 - 5. Sediment concentration during simulations on three land use types; forest, grassland and cropland

4.3.6 Effect of site characteristics and soil properties on soil erosion response

Table 4-6 shows the correlations and *p* values between site characteristics and sediment loss. The results indicate that slope, ground cover, and initial soil moisture content contribution in explaining variations in sediment concentration range from 32% to 57%. A study by Vermang *et al.* (2009) reported a decrease of soil erodibility with an increase in antecedent soil moisture content. The three factors explained 57% of the variation in sediment concentration from forest plots, 32% of variation from grassland plots and about 50% of variation from cropland plots. Slope steepness had a positive influence on sediment concentration with significant effects on forest and croplands, but not significant on grassland plots. Ground cover was negatively correlated to sediment concentration, with an increase in ground cover associated with a decrease in sediment concentration. Cerdà and Doerr (2007) reported that ground cover had a great influence on hydrological response and soil erodibility. Agricultural land use which often results in less ground cover was reported to result in higher soil erodibility compared with scrubland (Cerdà, 2000) and agriculture is associated with inducing long term soil degradation that increases runoff and soil losses (Barbera *et al.*, 2012; Ziadat and Taimeh, 2013). Initial soil condition affected sediment concentration and was significant for all three land use types. The results indicate that soil losses were lower during the wet runs compared to the dry runs. There was a decrease of about 32% in soil loss from plots within croplands (119 to 90 g/m^2), about 45% decrease from grasslands, and less significant decrease within forests. In experiments conducted in Kenya, Defersha and Melesse (2012) reported that higher sediment concentrations were found from plots with dry initial conditions compared to those from initially wet surfaces. Truman *et al.* (2011), reported an increase in runoff but decrease in sediments with increasing soil wetness. Ziadat and Taimeh (2013) reported that soil losses under cultivated lands increased as initial soil moisture conditions changed from dry, wet and very wet runs, in contrast to our results.

Table 4 - 6. Correlations and p values between site characteristics and sediment concentration

Parameter	Forest	Grassland	Cropland
Slope	r = + 0.59, p = 0.0001	Non-significant	r = 0.23, p = 0.0001
Ground Cover	r = -0.33, p=0.0001	r = -0.13, p= 0.0001	Non-significant
Initial Soil Moisture	r = 0.1, p= 0.016	r= + 0.36, p= 0.0001	R = + 0.17, p = 0.0079
R^2	0.57	0.32	0.50

Soil properties however, help to explain about 71% of variations on forest plots, 8% on grassland plots and about 48% on croplands. Significant soil properties include pH, bulk density, electrical conductivity and soil organic carbon. Soil texture seems to have an influence in sediment concentration with clay and sand showing significant influence on soil losses from forest and croplands, while silt had significance only on croplands.

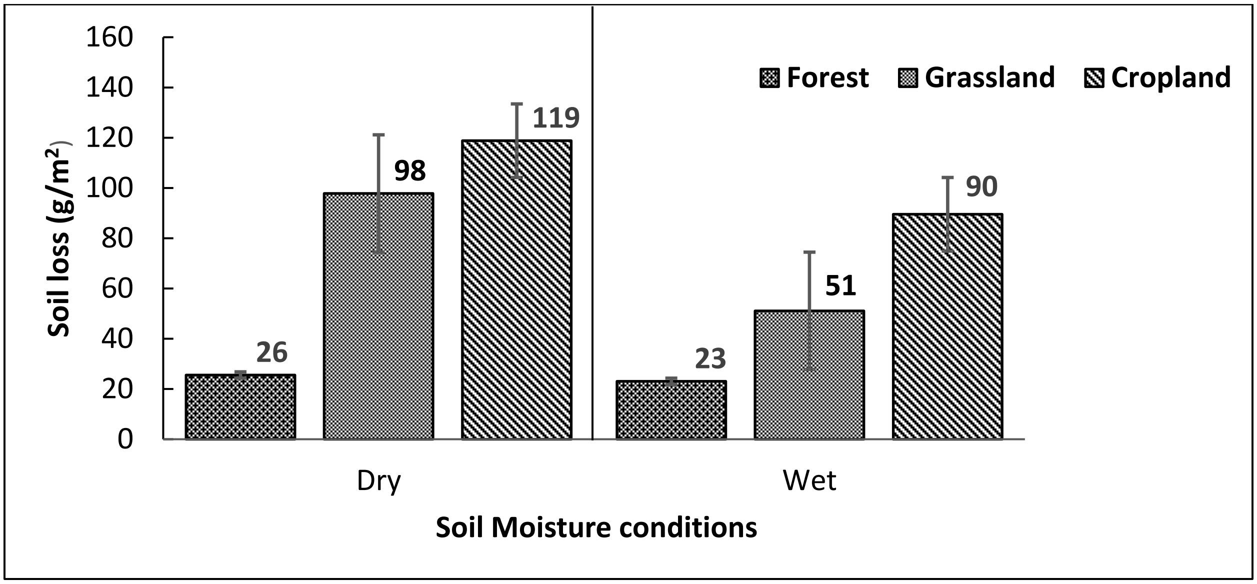

Figure 4 - 6. Sediment concentration from experiments under different initial soil moisture conditions

As expected, soil loss on steep slopes was higher compared to gentle slopes for all land uses (Figure 4-7). The influence of topography on soil erosion has been reported in other studies (e.g.,Joshi and Tambe, 2010; Martínez-Murillo *et al.*, 2013; Zhao *et al.*, 2013; Ziadat and Taimeh, 2013).

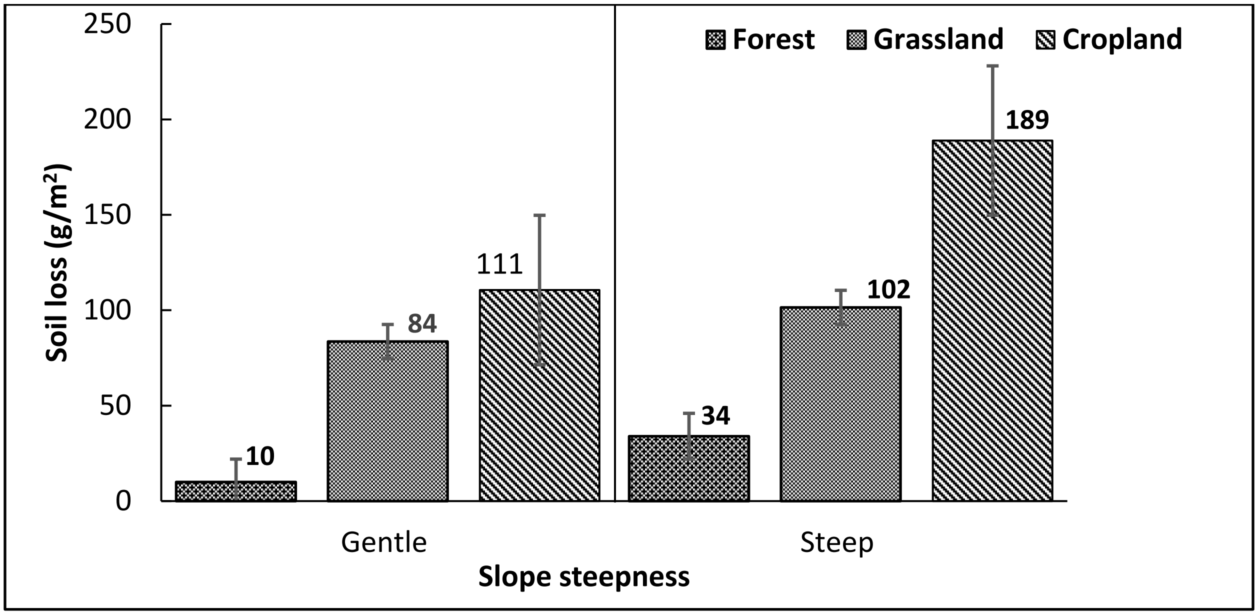

Figure 4 - 7. Sediment concentration from experiments under gentle and steep slopes

4.3.7 CN Estimation Results

Results of CN and characteristics of the sites are presented in Table 4-7. The CN for each site was determined using the runoff depths and rainfall depths obtained from the rainfall simulation experiment conducted for three land use types; upland rice, forest and grassland. The results show that the two upland rice sites had 85 and 91 CN values. CN values for grassland were 79 and 81, while forest sites had the lowest CN values of 49.2 and 66. In general higher CN values were found in the upland rice, this may be attributed to the lack of surface cover and therefore allowed more surface runoff from the plot. On the other hand the forest, had higher percentage cover and therefore less soil erosion from the plots. However, due to small number of samples, this was not tested. The results are within the ranges found in literature (Rawls *et al.*, 1980; USDA, 1986).

Table 4 - 7. CN Results from Experiments

Site	LULC	I_a (mm)	S (mm)	CN	MC (%)	%Cover	%Slope
1	Upland Rice	2.3	46.0	84.7	26.5	42.5	24.4
2	Upland Rice	1.3	26.0	90.7	24.1	45.0	27.4
1	Forest	6.7	134.0	65.5	22.3	90.0	20.8
2	Forest	13.1	262.0	49.2	27.7	76.7	31.5
1	Grassland	3.4	67.4	79.0	26.3	58.3	28.4
2	Grassland	3.0	60.0	80.9	24.8	80.0	24.6

4.4 Conclusions

Rainfall simulation experiments were conducted to quantify the impacts of three land use types (forests, grasslands and croplands), site characteristics (slope, ground cover, soil moisture content) and soil properties (texture, pH, Bulk density, and soil organic carbon) on runoff generation and soil erosion.

The runoff and sediment generation rates from the three land use types under different site characteristics show higher runoff rates (48.0 mm h^{-1}) from croplands compared to grasslands (24 mm h^{-1}) and forests (6 mm h^{-1}). Similarly, higher sediment concentrations (5.7 g/l) and higher soil loss rates (94 g/m^2) were measured from cropland plots than from grasslands (4.5 g/l for sediment concentrations and 66 g/m^2 for soil loss rate) and forests (1 g/l for sediment concentration and 24 g/m^2 for soil loss rates). Slope steepness, percentage ground cover, initial soil moisture content and soil properties were found to have minor to significant effects on runoff and soil loss variation across plots and runs. Higher soil loss rates of up to 306 g/m^2 were noted from croplands on steep slopes. It was found that slope was positively correlated to runoff and soil loss rates, suggesting that cultivation along high slope gradients may increase the runoff and sediment generation rates. Ground cover was found to be negatively correlated to runoff and soil loss for all land use types. The time for runoff to begin was found to be related to the initial soil moisture conditions. In this study it was found that dry initial soil moisture conditions result in higher soil erosion rates than wet initial conditions, suggesting that more soil erosion occurs at the beginning of the rainfall season when soil moisture conditions are dry.

The Curve Number runoff parameter, CN, was estimated for the three land use types; upland rice, grassland and forest. Results show high CN values in the upland rice and low CN values were found in the forest. This is not surprising results considering the influence of surface cover and soil moisture content as recognized by other researchers.

Results obtained from this study are preliminary and give a general trend of relative surface runoff and soil rates from dominant land use types. The results also provide useful information for understanding the hydrology of the upper Ruvu watershed and for validating hydrology and erosion models. The information for this study can be used as a base for devising strategies on soil conservation by designing farming practices that consider slope, increasing ground cover by mulching and agroforestry as well as afforestation of the disturbed landscapes. Further studies using different rainfall intensities involving other dominant land use types and management practices such as tillage practices and different vegetation cover are recommended.

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References

Arnaez J, Lasanta T, Ruiz-Flaño P, Ortigosa L. 2007. Factors affecting runoff and erosion under simulated rainfall in Mediterranean vineyards. Soil and Tillage Research, **93**: 324-334. DOI: http://dx.doi.org/10.1016/j.still.2006.05.013.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large area hydrologic modeling and assessment part I: Model development1. Wiley Online Library.

Barbera V, Poma I, Gristina L, Novara A, Egli M. 2012. Long-term cropping systems and tillage management effects on soil organic carbon stock and steady state level of C sequestration rates in a semiarid environment. Land Degradation & Development, **23**: 82-91.

Bates DM, Watts DG. 1988. Nonlinear regression: iterative estimation and linear approximations. Nonlinear Regression Analysis and Its Applications: 32-66.

Beven K, Binley A. 1992. The future of distributed models: Model calibration and uncertainty prediction. Hydrological Processes, **6**: 279-298. DOI: 10.1002/hyp.3360060305.

Beven KJ. 2011. Rainfall-Runoff Modelling: The Primer (2nd Edition). Wiley-Blackwell.

Boix-Fayos C, Martínez-Mena M, Arnau-Rosalén E, Calvo-Cases A, Castillo V, Albaladejo J. 2006. Measuring soil erosion by field plots: Understanding the sources of variation. Earth Science Reviews, **78**: 267-285. DOI: 10.1016/j.earscirev.2006.05.005.

Bosznay M. 1989. Generalization of SCS curve number method. Journal of irrigation and drainage engineering, **115**: 139-144.

Brown AM. 2001. A step-by-step guide to non-linear regression analysis of experimental data using a Microsoft Excel spreadsheet. Computer Methods and Programs in Biomedicine, **65**: 191-200. DOI: http://dx.doi.org/10.1016/S0169-2607(00)00124-3.

Bryan R. 1981. Soil erosion under simulated rainfall in the field and laboratory: variability of erosion under controlled conditions.

Burgess N, Doggart N, Lovett JC. 2002. The Uluguru Mountains of eastern Tanzania: the effect of forest loss on biodiversity. Oryx, **36**: 140-152.

Cerdà A. 2000. Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia. Soil and Tillage Research, **57**: 159-166.

Cerdà A, Doerr SH. 2007. Soil wettability, runoff and erodibility of major dry-Mediterranean land use types on calcareous soils. Hydrological Processes, **21**: 2325-2336. DOI: 10.1002/hyp.6755.

Christiansen JE. 1942. Irrigation by sprinkling. Univ. Calif. Agric. Exp. Stn. Bull. 670.

De Luis M, González-Hidalgo J, Longares L. 2010. Is rainfall erosivity increasing in the Mediterranean Iberian Peninsula? Land Degradation & Development, **21**: 139-144.

Defersha MB, Melesse AM. 2012. Field-scale investigation of the effect of land use on sediment yield and runoff using runoff plot data and models in the Mara River basin, Kenya. CATENA, **89**: 54-64. DOI: http://dx.doi.org/10.1016/j.catena.2011.07.010.

Descheemaeker K, Amede T, Haileslassie A, Bossio D. 2011. Analysis of gaps and possible interventions for improving water productivity in crop and livestock systems of Ethiopia Experimental Agriculture, **47**: 21-38. DOI: doi:10.1017/S0014479710000797.

Dillaha T, Ross B, Mostaghimi S, Heatwole C, Shanholtz V. 1988. Rainfall simulation: A tool for best management practice education. Journal of Soil and Water Conservation, **43**: 288-290.

Elhakeem M, Papanicolaou AN. 2009. Estimation of the Runoff Curve Number via Direct Rainfall Simulator Measurements in the State of Iowa, USA. Water Resour Manage, **23**: 2455-2473. DOI: 10.1007/s11269-008-9390-1.

Eshleman KN. 2013. Hydrological Consequences of Land Use Change: A Review of the State-of-Science. In: Ecosystems and Land Use Change, American Geophysical Union, pp: 13-29.

Flanagan D, Ascough J, Nicks A, Nearing M, Laflen J, Flanagan D, Nearing M. 1995. Overview of the WEPP erosion prediction model. Water erosion prediction project: hillslope profile and watershed model documentation. West Lafayette: United States Department of Agriculture/National Soil Erosion Research Laboratory: 1.1-1.12.

Fu S, Zhang G, Wang N, Luo L. 2011. Initial abstraction ratio in the SCS-CN method in the Loess Plateau of China. Transactions of the ASABE, **54**: 163-169.

Grismer M. 2012. Standards vary in studies using rainfall simulators to evaluate erosion. Calif Agr, **66**: 102-107.

Grismer ME. 2012. Erosion modelling for land management in the Tahoe basin, USA: scaling from plots to forest catchments. HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES, **57**: 878-900. DOI: 10.1080/02626667.2012.685170.

Gundalia M, Dholakia M. 2014. Impact of monthly curve number on daily runoff estimation for Ozat catchment in India. Open Journal of Modern Hydrology, **4**: 144.

Hartanto H, Prabhu R, Widayat AS, Asdak C. 2003. Factors affecting runoff and soil erosion: plot-level soil loss monitoring for assessing sustainability of forest management. Forest Ecology and Management, **180**: 361-374.

Hewlett JD. 1982. Principles of forest hydrology. University of Georgia Press.

Hudson BD. 1994. Soil organic matter and available water capacity. Journal of Soil and Water Conservation, **49**: 189-194.

Hudson N. 1961. An introduction to the mechanics of soil erosion under conditions of subtropical rainfall. Proc. Trans. Rhod. Sci. Assoc, **49**: 15-25.

Hughes D, Jewitt G, Mahé G, Mazvimavi D, Stisen S. 2015. A review of aspects of hydrological sciences research in Africa over the past decade. Hydrological Sciences Journal, **60**: 1865-1879.

Humphry JB, Daniel TC, Edwards DR, Sharpley AN. 2002. A portable rainfall simulator for plot-scale runoff studies. Applied Engineering in Agriculture, **18**.

IUCN. 2010. IUCN Eastern and Southern Africa Programme, 2010. The Ruvu Basin: A Situation Analysis., xvi + 96 pp. IUCN - ESARO Publications Service Unit

JICA. 2012. The Study on Water Resources Management and Development in Wami/Ruvu Basin in the United Republic of Tanzania. Ministry of Water (MoW).

Jones S. 1996. Discourses on land degradation in the Uluguru mountains, Tanzania: Evolution and influences. Journal of Rural Studies, **12**: 187-199. DOI: http://dx.doi.org/10.1016/0743-0167(96)00014-9.

Joshi V, Tambe D. 2010. Estimation of infiltration rate, run-off and sediment yield under simulated rainfall experiments in upper Pravara Basin, India: Effect of slope angle and grass-cover. J Earth Syst Sci, **119**: 763-773. DOI: 10.1007/s12040-010-0055-0.

Kibet LC, Saporito LS, Allen AL, May EB, Kleinman PJA, Hashem FM, Bryant RB. 2014. A Protocol for Conducting Rainfall Simulation to Study Soil Runoff. e51664. DOI: doi:10.3791/51664.

Kimaro DN, Poesen J, Msanya BM, Deckers JA. 2008. Magnitude of soil erosion on the northern slope of the Uluguru Mountains, Tanzania: Interrill and rill erosion. CATENA, **75**: 38-44. DOI: http://dx.doi.org/10.1016/j.catena.2008.04.007.

Knisel WG. 1980. CREAMS: A field-scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report.

Kosmas C, Danalatos N, Cammeraat LH, Chabart M, Diamantopoulos J, Farand R, Gutierrez L, Jacob A, Marques H, Martinez-Fernandez J, Mizara A, Moustakas N, Nicolau JM, Oliveros C, Pinna G, Puddu R, Puigdefabregas J, Roxo M, Simao A, Stamou G, Tomasi N, Usai D, Vacca A. 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. CATENA, **29**: 45-59. DOI: http://dx.doi.org/10.1016/S0341-8162(96)00062-8.

Loch RJ. 2000. Using rainfall simulation to guide planning and management of rehabilitated areas: Part I. Experimental methods and results from a study at the Northparkes Mine, Australia. Land Degradation & Development, **11**: 221-240. DOI: 10.1002/1099-145X(200005/06)11:3<221::AID-LDR381>3.0.CO;2-2.

Martínez-Murillo J, Nadal-Romero E, Regüés D, Cerdà A, Poesen J. 2013. Soil erosion and hydrology of the western Mediterranean badlands throughout rainfall simulation experiments: a review. Catena, **106**: 101-112.

McCuen RH. 2003. Modeling hydrologic change : statistical methods. Lewis Publishers.

Milliman JD, Meade RH. 1983. World-wide delivery of river sediment to the oceans. The Journal of Geology: 1-21.

Mishra S, Jain M, Singh V. 2004. Evaluation of the SCS-CN-based model incorporating antecedent moisture. Water Resour Manage, **18**: 567-589.

Mishra S, Sahu R, Eldho T, Jain M. 2006. An improved I a S relation incorporating antecedent moisture in SCS-CN methodology. Water Resour Manage, **20**: 643-660.

Mishra SK, Singh V. 2013. Soil conservation service curve number (SCS-CN) methodology. Springer Science & Business Media.

Moberg J. 2001. Soil and plant analysis manual. The Royal Veterinary and Agricultural University, Chemistry Department, Copenhagen, Denmark, **133**.

Moore ID, Hirschi MC, Barfield BJ. 1983. Kentucky rainfall simulator. Transactions of the ASAE, **26**: 1085-1089.

Msaghaa JJ, Melesse AM, Ndomba PM. 2014. Modeling Sediment Dynamics: Effect of Land Use, Topography, and Land Management in the Wami-Ruvu Basin, Tanzania. In: Nile River Basin, Springer, pp: 165-192.

Mutchler CK, Hermsmeier. 1965. A Review of Rainfall Simulators. Transactions of the ASAE, **8**: 67-68. DOI: doi: 10.13031/2013.40428 (1965).

Ngoye E, Machiwa JF. 2004. The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Physics and Chemistry of the Earth, Parts A/B/C, **29**: 1161-1166. DOI: http://dx.doi.org/10.1016/j.pce.2004.09.002.

Nishigaki T, Sugihara S, Kilasara M, Funakawa S. 2016. Surface Runoff Generation and Soil Loss Under Different Soil and Rainfall Properties in The Uluguru Mountains, Tanzania. Land Degradation & Development: n/a-n/a. DOI: 10.1002/ldr.2499.

Novotny V. 2003. Water quality: Diffuse pollution and watershed management. 2 Edn., J. Wiley & Sons.

Nunes AN, de Almeida AC, Coelho COA. 2011. Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. Applied Geography, **31**: 687-699. DOI: http://dx.doi.org/10.1016/j.apgeog.2010.12.006.

Okelo M, Onyando J, Gichaba C, Shivoga W, Miller S. 2005. Micro-field assessment of soil erosion and surface runoff using mini rainfall simulator in upper River Njoro watershed.

Peng T, Wang S-j. 2012. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. CATENA, **90**: 53-62. DOI: http://dx.doi.org/10.1016/j.catena.2011.11.001.

Rapp A, Berry L, Temple P. 1972. Studies of soil erosion and sedimentation in Tanzania. Bureau of Resource Assessment and Land Use Planning, University of Dar es Salaam.

Rawls WJ, Onstad CA, Richardson H. 1980. Residue and tillage effects on SCS runoff curve numbers. Transactions of the ASAE, **23**: 357-0361.

Saxton K, Rawls W. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil science society of America Journal, **70**: 1569-1578.

Schindewolf M, Schmidt J. 2012. Parameterization of the EROSION 2D/3D soil erosion model using a small-scale rainfall simulator and upstream runoff simulation. CATENA, **91**: 47-55. DOI: http://dx.doi.org/10.1016/j.catena.2011.01.007.

Sharpley A, Daniel T, Wright B, Kleinman P, Sobecki T, Parry R, & Joern, B. 1999. National research project to identify sources of agricultural phosphorus loss. Better Crops, **83**: 12-14.

Sharpley AN, Kleinman P, McDowell R. 2001. Innovative management of agricultural phosphorus to protect soil and water resources. Commun Soil Sci Plan, **32**: 1071-1100.

Sole´-Benet A, Calvo A, Cerda A, La´zaro R, Pini R, Barbero J. 1997. Influences of micro-relief patterns and plant cover on runoff related processes in badlands from Tabernas (SE Spain). CATENA, **31**: 23-38. DOI: http://dx.doi.org/10.1016/S0341-8162(97)00032-5.

Srinivasan MS, Kleinman PJA, Sharpley AN, Buob T, Gburek WJ. 2007. Hydrology of Small Field Plots Used to Study Phosphorus Runoff under Simulated Rainfall All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. J. Environ. Qual., **36**: 1833-1842. DOI: 10.2134/jeq2007.0017.

Temple PH. 1972. Soil and Water Conservation Policies in the Uluguru Mountains, Tanzania. Geografiska Annaler. Series A, Physical Geography, **54**: 110-123. DOI: 10.2307/520762.

Truman C, Potter T, Nuti R, Franklin D, Bosch D. 2011. Antecedent water content effects on runoff and sediment yields from two Coastal Plain Ultisols. Agricultural Water Management, **98**: 1189-1196.

URT. 2011. United Republic of Tanzania (2011). Morogoro District Profile, Prime Minister's Office: Ministry of Regional Administration and Local Government, Morogoro, Tanzania.

USDA. 1986. Urban hydrology for small watersheds. Technical release, no 55 (TR-55). US Dept. of Agriculture, Soil Conservation Service, Engineering Division.

Vermang J, Demeyer V, Cornelis W, Gabriels D. 2009. Aggregate stability and erosion response to antecedent water content of a loess soil. Soil Science Society of America Journal, **73**: 718-726.

Vrieling A. 2006. Satellite remote sensing for water erosion assessment: A review. CATENA, **65**: 2-18. DOI: 10.1016/j.catena.2005.10.005.

Walsh R, Coelho C, Elmes A. 1998. Rainfall simulation plot experiments as a tool in overland flow an soil erosion assessment, North-Central Portugal.

Wischmeier W, Smith D. 1978. Predicting rainfall erosion losses: A guide to conservation planning U.S. Department of Agriculture

Woodward DE, Hawkins RH, Jiang R, Hjelmfelt AT, Van Mullem JA, Quan QD. 2003. Runoff curve number method: examination of the initial abstraction ratio. In: World Water & Environmental Resources Congress 2003, ASCE, pp: 1-10.

WRBWO. 2008. Wami /Ruvu Basin Water Office (WRBWO). 2008. Business Plan.

Yanda P, Munishi P. 2007. Hydrologic and Land Use/Cover Change Analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) Watersheds. For WWF/CARE Dar es Salaam, Tanzania.

Zhao N, Yu F, Li C, Wang H, Liu J, Mu W. 2014. Investigation of Rainfall-Runoff Processes and Soil Moisture Dynamics in Grassland Plots under Simulated Rainfall Conditions. Water, **6**: 2671-2689.

Zhao XI, Wua P, Chen XL, Helmers MJ, Zhou XB. 2013. Runoff and sediment yield under simulated rainfall on hillslopes in the Loess Plateau of China. SOIL RESEARCH, **51**: 50-58. DOI: 10.1071/SR12239.

Ziadat F, Taimeh A. 2013. Effect of rainfall intensity, slope, land use and antecedent soil moisture on soil erosion in an arid environment. Land Degradation & Development, **24**: 582-590.

Chapter 5. Modeling Streamflow Response to Changes in Land Use and Land cover in the Upper Ruvu Watershed, Tanzania

Abstract

Changes in land use and land cover (LULC) as a result of population increase have far reaching consequences on various landscapes and watershed functions in Tanzania. LULC directly impacts hydrologic processes leading to changes in streamflow at sub-watershed and watershed scales. In this study, the Soil Water Assessment Tool (SWAT) was used to assess the impacts of LULC change on streamflows in the Upper Ruvu watershed in Tanzania which has endured significant land alterations in the last three decades. Calibration and uncertainty analysis of the model was performed with the Calibration and Uncertainty Programs (SWAT-CUP) using the Sequential Uncertainty Fitting version 2 (SUFI-2). Daily simulation results from January 1973 to December 1977 were used for model calibration, and evaluation was based on the period from January 1978 to December 1982. Plausible model performance was achieved for simulated daily streamflow through comparison with measured streamflow from two gauging stations with the Nash-Sutcliffe Efficiency (NSE) of 0.69 and 0.84 during calibration and 0.68 and 0.67 during evaluation. In addition, model performance was evaluated using percent bias (PBIAS), ratio of root mean square error to the standard deviation of measured data (RSR), and the correlation coefficients (R^2) which all indicated reasonable predictions. The calibrated model was used to investigate streamflow response to changes in land use between 1991 and 2015. Long term average annual streamflow simulation between 1991 and 2000 showed a slight decrease (2%) from 47.41 m^3s^{-1} to 46.32 m^3s^{-1}. Average streamflow simulation between 1991 and 2015 showed a 13% decrease (from 47.41 m^3s^{-1} to 41.50 m^3s^{-1}). Average peak flows increased by 5% and 12% for 2000 and 2015, respectively compared to the baseline. Land alterations had significant impacts on surface runoff which increased by 75% in 2015 from the baseline period. The land alterations had impacts on baseflow with declines of 43% by 2000 and 66% by 2015. High amount of surface runoff was generated in the upstream and areas in the Uluguru Mountains. These results reveal the dominant role land use plays in the hydrology of the watershed and has provided quantitative information for decision makers and water managers.

Key words: **land use, land cover change, SWAT, streamflow, modeling, Upper Ruvu, watershed management, surface runoff**

5.1 Introduction

Human induced land use and land cover (LULC) alterations affect the structure and hydrological properties of soil and vegetation layers (Hornbeck *et al.*, 1993; Yang *et al.*, 2015). LULC changes can result in the loss of forest cover and can affect watershed hydrological processes in different ways including changes on evapotranspiration, interception, infiltration, surface runoff and groundwater recharge, all of which subsequently change the timing and magnitude of streamflow (Fohrer *et al.*, 2001; Baker and Miller, 2013; Eshleman, 2013). A decrease in interception due to loss of vegetation cover during high rainfall events can result in rapid movements of water when the infiltration is exceeded causing floods and altering flow regimes (Calder *et al.*, 1995). Changes in land use and land cover do not only result in disturbance of the watershed's ability to provide ecosystem functions and services (Carpenter *et al.*, 1992; Tang *et al.*, 2005; Zhao *et al.*, 2012), but also contributes to land degradation and environmental pollution (Foley *et al.*, 2005).

The Uluguru Mountains in Morogoro, Tanzania, along with surrounding areas including the montane forests are renowned for a high level of endemism among plants and terrestrial fauna and are recognized as one of the important conservation sites in the world (Burgess *et al.*, 2002). The Ruvu River, which is an important source of water supply for commercial and domestic purposes for the main city of Dar es Salaam and surrounding areas, has its headwater streams originating in the rain forests of the Uluguru Mountains. In the past four decades, the Eastern Arc Mountains including the Uluguru Mountains landscapes have undergone changes as a result of anthropogenic activities. Disturbances such as encroachment on forest areas through pit sawing, harvesting for building materials, medicinal, charcoal burning, and firewood (Yanda and Munishi, 2007). Agriculture, especially shifting cultivation is practiced in the landscape because of the availability of fertile soils and water (Burgess *et al.*, 2002; Yanda and Munishi, 2007). The landscape degradation has largely been exacerbated by the increase in population as more people move in search of fertile soils and suitable rainfall. In recent years movement of livestock herds from outside the watershed to the foothills and lowland areas have also increased (IUCN, 2010). It is estimated that approximately 60% of the watershed's population live along the slopes of Uluguru Mountains (URT, 2011), and depend on the landscapes' natural resources.

Yanda and Munishi (2007), reported a decrease of forest and woodlands of between 2% and 20% for 1995 and 2000 respectively in the Ruvu River basin. Land use and land cover mapping done as part of this study (see Chapter 2) found that natural forests decreased by 77% between 1991 and 2015. In addition, a decrease of 44% was found in woodland, and increases of 110% and 72% were reported in cropland and grassland respectively for the same time period. As agricultural practices in the area involve shifting cultivation with limited use of conservation techniques, the land is left exposed to erosion agents resulting in soil quality deterioration and subsequent decline in crop yield. As a result, most farms are abandoned and farmers clear a new piece of land for cultivation which further degrade the landscapes. The human activities have consequences on the availability of water to people and the environment, not only in the watershed but also in downstream rural and urban areas. Declining water flows especially in the dry season have been reported in the downstream part of the watershed (Yanda and Munishi, 2007; IUCN, 2010). Although declining streamflows can caused by other factors including increased water abstraction, but the role of human activities is worth an investigation.

Given the rapid increase in population seen in recent decades and the subsequent loss of natural land cover, knowledge of the plausible impacts of LULC change on streamflow and overall hydrology is important. Numerous studies have revealed the relationship between LULC and various aspects of hydrology including streamflow (Costa *et al.*, 2003; Legesse *et al.*, 2003; Ma *et al.*, 2008; Breuer *et al.*, 2009; Mueller *et al.*, 2009; Ghaffari *et al.*, 2010; Mango *et al.*, 2010; Babar and Ramesh, 2015). Methods such as paired watersheds (Brown *et al.*, 2005), statistical analyses and hydrological models (Eshleman, 2013) have been employed in the investigation of impacts of deforestation, afforestation and land conversions on hydrology. In Tanzania, the catchment studies on the effects of deforestation/afforestation on catchment discharge started back in the 1960s. Plantation forest and tea were found to have small effects on streamflow once plant canopy completely covered the ground and had established a deep rooted system (Dagg and Blackie, 1965). Edwards and Blackie (1981), recorded 50% increase in streamflow in cleared forest compared with the control. (Bosch and Hewlett, 1982) and Hibbert (1965) showed that increase in forest cover can cause a decrease in water discharge due to increased evapotranspiration. Other studies in the tropics using paired watersheds have been inconclusive (Baker and Miller, 2013). Although, paired watersheds can provide direct evidence of the influence of land use change on streamflow, they generally require long time of monitoring, cover only a small area, may be difficult to replicate and it is sometimes difficult to find comparable paired watersheds, as it is well documented that the watershed hydrology is affected by vegetation types, soil properties, geology, terrain, climate, land use practices, and spatial patterns of interactions among these factors (Tomer and Schilling, 2009).

Hydrologic models are now regarded as powerful tools for investigating the impacts of changes in land use and land cover on streamflow and hydrology of watersheds (Biftu and Gan, 2001; Veldkamp and Lambin, 2001; Legesse *et al.*, 2003). However, such models require extensive data sets that are sometimes difficult to find in developing countries like Tanzania (Ndomba *et al.*, 2008; Natkhin *et al.*, 2015). Despite the scarcity of long-term observed data available to assess changes in water resources in Tanzania, several studies have showed promising results using the Soil and Water Assessment Tool (SWAT) for understanding hydrological processes of watersheds in Tanzania and East Africa (e.g., Mulungu and Munishi, 2007; Ndomba *et al.*, 2008; Birhanu, 2009; Natkhin *et al.*, 2014; Natkhin *et al.*, 2015). On the other hand, attempts to describe the impacts of land conversion and forest loss on watershed hydrology has been done only using qualitative approaches (Yanda and Munishi, 2007). However, it is realized that despite the challenges, there is a clear motive for finding answers to the problems in hydrology.

In this study we use the SWAT model (Nietsch *et al.*, 2001; Arnold and Fohrer, 2005) to examine the streamflow responses to changes in land use and land cover in the Upper Ruvu Watershed for the past 25 years. This information is crucial for planning and water resources management and the need to quantify the extent to which land use and climate influence the hydrological conditions is deemed necessary. The SWAT model is an effective tool for simulating rainfall-runoff relationships under land use changes on the water cycle (Fohrer *et al.*, 2001; Tripathi *et al.*, 2005).

5.2 Materials and Methods

5.2.1 Description of the study area

The Upper Ruvu watershed is located in Morogoro Rural District in Morogoro Region,Tanzania. The watershed lies between latitudes 7^o 00’ and 7^{o}11’23.5”S and longitudes 37^{o}30’ and 37^{o}38’36.6”E, (Figure 5-1). The watershed covers an an area of approximately 7510 Km^2. The Ruvu River is an important source of water supply for Dar Es Salaam city and coast region.

Major tributaries of the watershed are the Mgeta in the western region and Ruvu, which comprises the Mvuha, Mmanga, Mfizigo and Mbezi located on the eastern region, meet to form the main Ruvu river at the confluence downstream (WRBWO, 2008; IUCN, 2010).The Ruvu river traverses through the landscapes dominated by forests, shrubland woodlands, grasslands and agricultural lands. This study found that agriculture is the dominant land use in the watershed occupying approximately 30% of the watershed area, followed by shrubland (21%) and grassland (20%) . The main crops are maize which are cultivated in the uplands and lowlands, rainfed upland rice which is common in the upland areas and paddy in the lowlands and wetlands. Other crops include banana, vegetables, roots and tubers, pineapples and spices.

The rainfall distribution pattern in the watershed is bi-modal with the main rainy season from March to May (MAM) locally known as the *masika*, and peak in April, whereas the short rains usually start in October and end in December (OND) locally known as the *vuli*, which are mainly controlled by the global circulation patterns. In comparison to the other watersheds forming the Ruvu River Basin, Upper Ruvu receives higher amount of rainfall. The mean annual rainfall varies between 750 and 1500 mm/year over most parts of the watershed but rises to over 2000 mm/year in the Uluguru Mountains, for stations such as Mondo, Hobwe and Morning side. Lowlands immediately adjacent to these mountains have less precipitation.

The bimodal pattern is usually associated with the northward and southward movement of the Intertropical Convergence Zone (ICTZ) and the El Nino-Southen Oscillation (ENSO) or other oceanic or atmospheric signals as well as the topography. Winds blowing from the Indian Ocean lose much of their moisture in the Uluguru Mountains in the form of orographic rain. The *La Nina winds* are responsible for drought in dry years. Temperature in the study area is variable with the mean monthly temperature ranging from 17.4^o C (July) to 22.4^o C (December).

The geology of the watershed can be grouped into: Precambrian, Karoo, Jurassic, Cretaceous, Tertiaty and Quaternary rocks. The occurrence of the precambrian is mainly in the Uluguru Mountains and can be divided into three major lithological groups: acid gneisses, granulites and crystalline limestone, which were thrust and uplifted by the upward movement of the basic gneisses, thus giving rise to distinct fault zone in the rocks (IUCN, 2010; JICA, 2012). The Karoo rocks occurs in the southern area of the Uluguru Mountains consisting mainly of sandstone and shale which was originally deposited in shallow fresh to brackish water. Jurassic rocks occur in the eastern margin of the Uluguru Mountains.They consist of course sandstone, mudstone and oolitic limestone deposited under the marine environment. Cretaceous rocks, which lie on the elevated rolling hills, consist of clay, shale, calcerous sandstone, sandy limestone and mudstone.

Sediments of Tertiary and Quaternary occur in the elevated rolling hills and along the Ruvu River flood plain (IUCN, 2010).

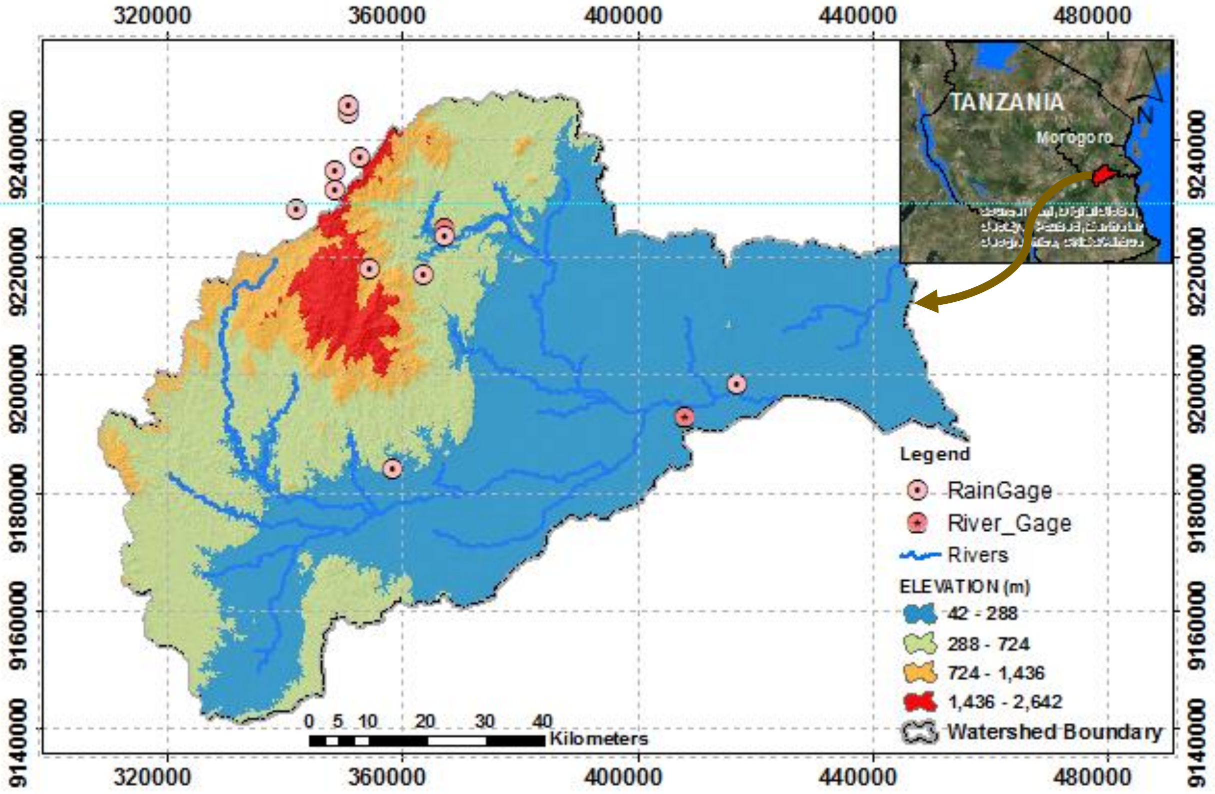

Figure 5 - 1. Location map of the study watershed showing elevation, meteorological and discharge stations

5.2.2 Hydrological Modeling

SWAT is a semi-distributed model and its use spans over three decades since its development by the United States Department of Agriculture (USDA). SWAT has received world wide application for predicting long term effects of land use/cover on water, sediment, point and non-point pollution even in complex watersheds (Arnold and Fohrer, 2005; Mueller *et al.*, 2009; Cai *et al.*, 2012). In the model, a watershed is divided into several sub-basins and further subdivided into Hydrologic Response Units (HRUs), which are represented as homogeneous soil, land use, and terrain characteristics. SWAT requires spatial data for soils, land use/management and topography. Climate data used by the model includes precipitation, temperature, relative humidity, solar radiation, and wind speed. The model uses the SCS CN (curve number) method to calculate runoff. The SCS CN method has been described and applied in several studies (e.g., Bondelid *et al.*, 1982; Cronshey, 1986; Lenhart *et al.*, 2002). The SCS runoff equation estimates event (or daily) runoff as:

$$Q_{Sur} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \tag{5-1}$$

where Q_{sur} is the runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), S is the retention parameter (mm), and is defined as:

$$S = 25.4 * \left(\frac{1000}{CN} - 10 \right) \tag{5-2}$$

The SCS curve number (CN) is a function of soil permeability, land use and antecedent soil moisture conditions. In the SWAT model, the main basin is divided into sub-basins by selecting points on the stream network that act as outlets. This selection allows the model to provide output at specific points of the river network. The variables such as water yield, sediment, nutrient, groundwater recharge, surface runoff are determined for each HRU and are then aggregated at the sub-basin level and routed in the river channel to the outlet (Arnold *et al.*, 1998). The water balance in the SWAT model is simulated based on the equation by Nietsch *et al.* (2001).

$$SW_t = SW_{\Delta t} + \sum_{i=1} (R_{day} - Q_{surf} - ET_i - W_{seepi} - Q_{gw}) \tag{5-3}$$

where SW_t is the soil water content (mm) on day t, $SW_{\Delta t}$ the initial soil water content on day i(mm), t the time (days), R_{day} the precipitation on day i (mm), Q_{surf} the surface runoff on day i (mm), ET_i the evapotranspiration on day i (mm), W_{seepi} the amount of water entering the vadose zone from the soil profile on day i (soil interflow) (mm) and Qgw the amount of return flow on day *i* (mm).

This study used the SWAT2012 version of the model along with its ArcMap interface (ArcSWAT 10.2) (Arnold *et al.*, 2012). The ArcSWAT interface extracts hydrologic information from spatial data, assigns parameter values based on soil and land cover, and uses the information for building needed SWAT input files. Several processes are used for calculating different components in the SWAT model. Most common hydrological equations for simulations of flow are incorporated in the SWAT model. However, these mathematical equations incorporated for representing different hydrological processes are only accurate if detailed input data are available. The main inputs that determine the usefulness of the SWAT model include the Digital Elevation Model (DEM) of the watershed, the soil and land use data and data representing the climate of the area. In the SWAT model, the land uses of a given watershed is assigned to land use types in the model database. The different land use types in the model have each a CN associated with them to determine the antecedent soil moisture assigned. Potential evapotranspiration in the model is estimated using one of the following four methods: Hargreaves (Hargreaves and Samani, 1985), Penman-Monteith (Monteith, 1965), Priestley Taylor (Priestley and Taylor, 1972), or read-in as Potential Evapotranspiration (PET). The leaf area index is simulated as a function of heat units and varies between plant-specific potential minimum and maximum values. Canopy evaporation is a function of potential evapotranspiration, maximum interception capacity and the ratio of the actual to potential maximum leaf area index. Plant water uptake from the soil is simulated as a function of potential evapotranspiration, leaf area index and rooting depth, and is limited by water content (Arnold and Fohrer, 2005).

5.2.3. Model input and Set UP

SWAT requires detailed inputs such as climatic conditions, soil, topography, topology, vegetation and land management.

Digital Elevation Model

We used a 30-m resolution digital elevation model (DEM) from the Shuttle Radar Topography Mission (available from www.earthexplorer.usgs.gov). The DEM was used to delineate sub-basins and to determine various topographic attributes (area, slope, slope length) and characteristics of the channel network including length, width and mean slope gradient (Chaplot *et al.*, 2006).

Land Use

Land use is an important factor that affects surface erosion, runoff, and evapotranspiration in a watershed. Land use maps used in this study were developed based on Landsat TM, ETM+ and Landsat 8 for 1991, 2000 and 2015 respectively. In mapping the land use, eight different land cover classes were identified as natural forest, shrubland, agriculture, woodland, grassland, bare land, wetlands and water. There was a significant loss of forest and woodland to agriculture and grassland during the 25 year time period (Figure 5-2). The details of the methodology are described in Chapter 2.

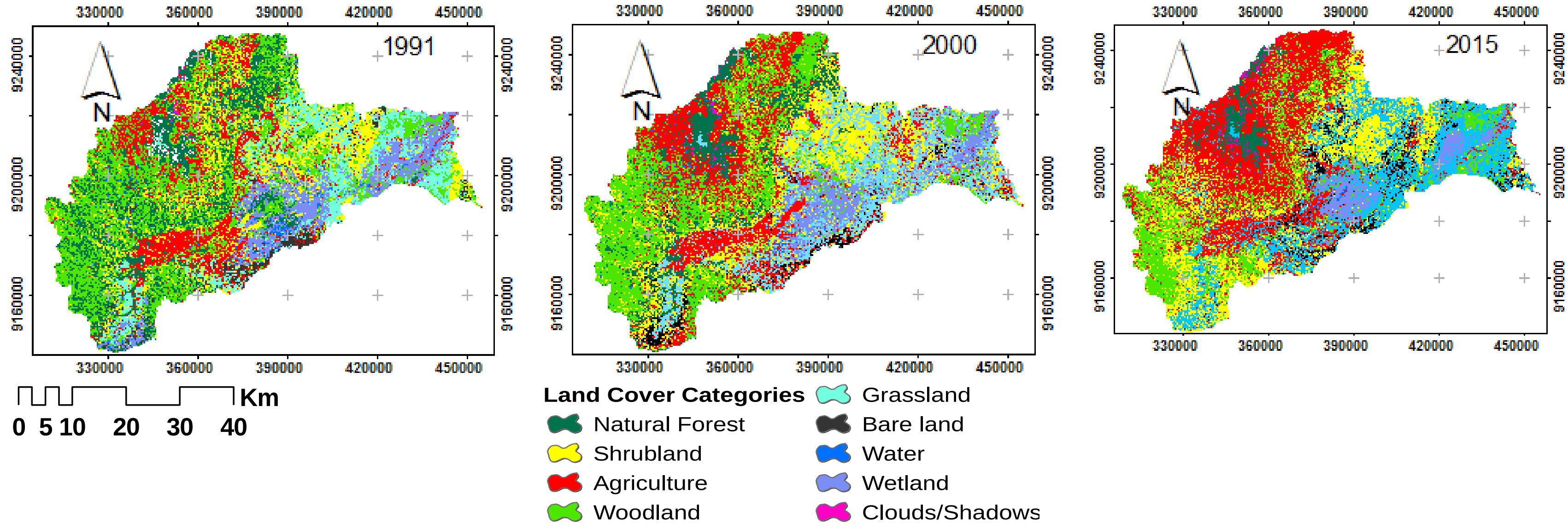

Figure 5 - 2. Land Use and Land Cover maps of Upper Ruvu watershed for 1991, 2000 and 2015.

Soils

The soil map for this study (Figure 5-3) was made from the 1984 Soils and Physiography of Tanzania (De Pauw, 1984). The soil input (.sol) in SWAT requires information on physical properties for all layers in the soil. The information was obtained from different sources: Soil and Terrain Database for Southern Africa (SOTER) (Batjes, 2004), from field soil sampling as part of this study , and data from the literature (JICA, 2012; Msaghaa *et al.*, 2014). The information was used to build the database needed by SWAT. There are seven major soils in the watershed: Acrisols (9.6%), Cambisols (21.2%), Ferrasols (24.5%), Fluvisols (18.9%), Leptosols (2.1%), Planosols (8.9%) and Vertisols (4.2%).

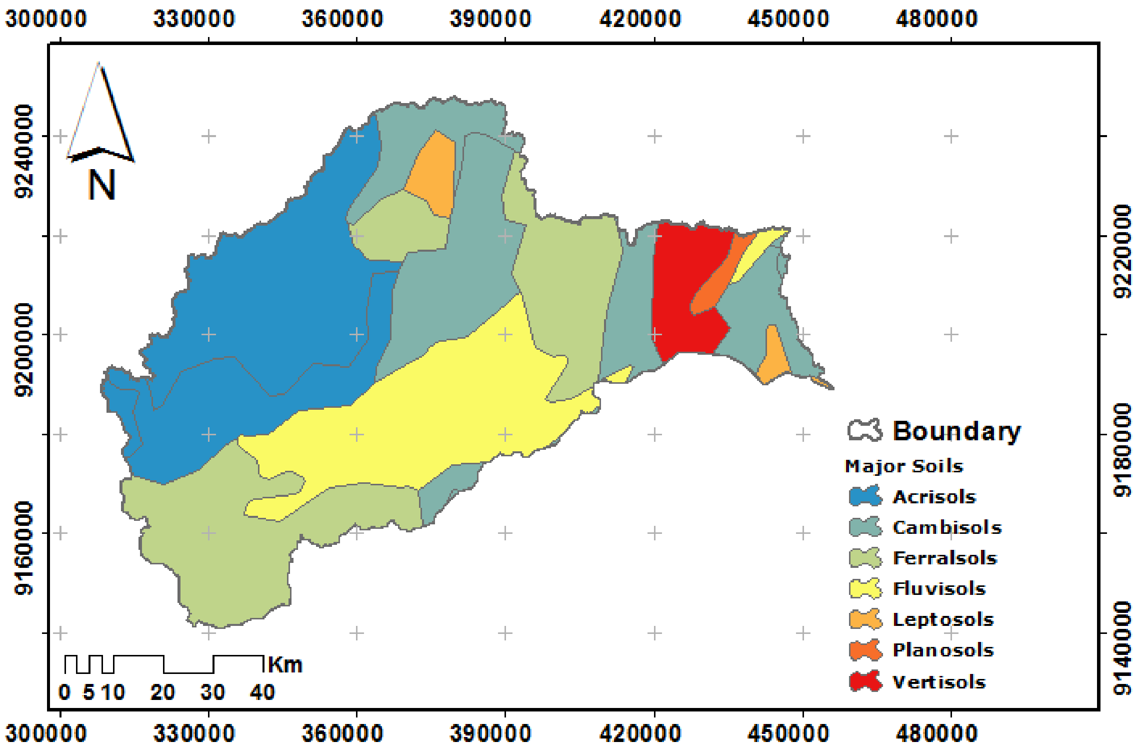

Figure 5 - 3. Soil map of the study area showing major soil types.

Weather data

Daily meteorological data collected from the Wami Ruvu Basin Water Office (WRBWO) and the Tanzania Meteorological Agency (TMA) were collated and assessed for accuracy and consistency. A total of 11 rain stations with at least 30 years of daily rainfall data are available from within and around the study area (Table 5-1). Most of the stations are located in the upper part of the watershed. Daily minimum and maximum temperature, solar radiation, relative humidity, and wind speed were obtained from the Morogoro Meteorological station. Missing data in the historical data were filled by regression equations of neighboring stations and were simulated using the WEXGEN stochastic weather generator model within the SWAT model based on 13 years of data from Morogoro (Neitsch *et al.*, 2002). The WEXGEN model uses monthly statistics calculated from daily weather data to fill in missing daily climate data or can simulate long term weather sequences based on these statistics.

Table 5 - 1. Rainfall Stations in the Upper Ruvu Watershed

No	ID	Station	Latitude	Longitude	Altitude	Ann.Rainfall (mm)*	Start	End
1	9637046	Morning Side	-6.90	37.67	1450	2217.0	1966	2012
2	9737076	Morogoro	-6.83	37.65	526	817.0	1971	2012
3	9737006	Matombo	-7.08	37.77	390	1547.1	1973	2012
4	9637045	Mondo	-6.95	37.63	1120	2384.3	1970	2012
5	9637048	Ruhungo	-6.92	37.63	880	979.2	1971	2012
6	9737026	Kibungo	-7.02	37.80	270	1519.4	1971	2012
7	9637052	Moro WD	-6.82	37.65	510	728.8	1956	2010
8	9000064	Mikula	-7.25	38.25	80	765.2	1976	2013
9	9737005	Singiza	-7.38	37.72	460	1325.4	1973	2007
10	9637047	Hobwe	-6.98	37.57	740	917.5	1971	2012
11	9637051	Mlali	-6.97	37.53	598	758.4	1956	2010

Discharge data

Observed discharge data for two gaging stations (i.e. 1H5 Ruvu River at Kibungo Bridge and 1H10 Ruvu at Mikula) were available (Table 5-2). Discharge data for the two stations were available from 1952, and water level data were available for years after 1989, but with a significant amount of missing data. We selected a period starting from 1971 to correspond with the rainfall data and meteorological data available in the watershed for model calibration and evaluation.

Table 5 - 2. Flow Stations in the Upper Ruvu Watershed

No	ID	Flow Station	Latitude	Longitude	Altitude	Area	Start	End
1	1H5	Ruvu-Kibungo	-7.01	37.8	474	420	1952	1987
2	1H10	Ruvu-Mikula	-7.3	38.17	80	5870	1966	1989

In SWAT, the HRU management file is used to summarize land use characteristics for different crops, including the crop calendar with information on tillage, planting, fertilizer, irrigation applications, nutrient applications and pesticide applications. SWAT uses three databases to store information required for plant growth, urban land characteristics and fertilizer components. We defined Management operations for three dominant crops (maize, banana and upland rice) in the Upper Ruvu watershed based on information from interviews in the field with secondary information obtained from the district agricultural office in Morogoro and the Wami Ruvu Basin Water Office. Maize which is dominantly cultivated in the uplands and lowlands is usually common in the long rainy season (March-May) with farm preparations starting in early February. Upland rice is dominant in the slopes and is usually planted in February. The watershed was discretized into 40 sub-basins and further into 1107 HRUs based on the combination of land use and soil type.

5.2.4 Parameter Sensitivity Analysis

The SWAT model comprises several parameters which represent the different hydrological conditions and characteristics across the watershed. The calibration process involved first defining and choosing the most sensitive parameters through sensitivity analysis. Sensitivity analysis is important in understanding model performance and reveals which parameters are mostly significant to the output variance due to input variability (Abbaspour et al., 2007) of most important parameters. It was applied to limit the number of optimized parameters required to obtain a good fit between the simulated and observed streamflow data. In this study, sensitivity analysis was carried out with a combined Latin hypercube and one-factor-at-a-time (LH-OAT) (van Griensven et al., 2006) sampling methods implemented in the SWAT-CUP (Calibration and Uncertainty Program for sensitivity analysis, calibration and uncertainty analysis). SWAT-CUP is a public domain program linking SUFI-2 (Sequential Uncertainty Fitting version 2) procedure to SWAT (Abbaspour et al., 2007). SUFI-2 incorporates both manual and auto-calibration procedures including the sensitivity and uncertainty analysis (Arnold et al., 2012). This allows users to manually adjust some parameters and ranges iteratively between auto-calibration runs. SUFI-2 has been successfully used for case studies in Africa and Asia, and the US (Schuol *et al.*, 2008; Abbaspour *et al.*, 2009; Faramarzi *et al.*, 2009; Betrie *et al.*, 2011; Arnold *et al.*, 2012). The NSE coefficient was used as an objective function during the sensitivity analysis. SUFI-2 uses the t-statistic and p-value to rank the sensitivity of parameters. The parameter with the highest absolute value of t-stat and the smallest p-value is considered the most sensitive parameter. The most sensitive parameters usually appear with p-values less than the alpha level of 0.05. Streamflow data and climate data from January 1973 to December, 1977 were used to run the model for sensitivity analysis using default model parameters. The default parameters are based on literature and on the range suggested in the SWAT user's manual (Neitsch *et al.*, 2002).The results of the sensitivity tool provide general adjustments guidelines and reduce time-required for calibration.

5.2.5 Model calibration and evaluation

The model was set up and run at a daily time step for the period from 1971 to correspond with the weather data. A "warm-up" of two years was used (January 1971 to December 1972) and a 5-year period for calibration of flow (January 1973 to December 1977). Based on the available data and parameters, the calibration was performed for streamflow. The model was calibrated by comparing with measured daily streamflow at two gauging stations; 1H5 (Ruvu River at Kibungo Bridge) representing the upstream part of the watershed and 1H10 (Ruvu River at Mikula) located in the downstream part of the watershed and is considered as an outlet of the watershed. Model evaluation to test how well the calibrated results matched the observed streamflow data at the two gauging stations was done for 5 years from January 01, 1978 to December, 31, 1978. However, due to the presence of suspicious high peaks of streamflow data recorded at the end of 1978 and early in 1979, the period of (Nov 1, 1978 to Aug 22, 1979 was removed from the time series and not used for model evaluation. Apart from calibrating for flow, evapotranspiration was considered during the calibration and evaluation processes. The potential evapotranspiration was calculated by Penman-Monteith Equation (Allen *et al.*, 1998), using data from 1971 to 2012 for Morogoro station. Potential evapotranspiration of 1509 mmyr^{-1} was estimated for the Morogoro station (Figure A-6).

5.2.6 Curve number selection

SCS CN for the Upper Ruvu watershed based on the land use and hydrologic soil groups of the Upper Ruvu watershed were selected using guidelines from published tables (USDA, 1986; Rawls *et al.*, 1992). Hydrologic soil groups for the major soils found in the watershed were grouped and in combination with land use maps, the CN for different land cover were assigned as shown in Table 5-3. The SCS curve number is a function of the soil's permeability, land use and antecedent soil moisture conditions and are therefore expected to differ as conditions such as land use and land cover change. Field experiments to estimate CN from three land use types (forest, grassland and upland rice) were carried out in some parts of the watershed, and helped to shed lights on the variation of CN for various land use types. The range of the CN values from the three land use types investigated during the field experiments range between 30 and 33 for forests, 54 and 61 for grassland and between 78 and 90 for croplands.

Table 5 - 3. CNs for the Upper Ruvu Watershed

LULC	Hydrologic Soil Group			
	A	B	C	D
Natural Forests	30	30	41	48
Bushland	49	69	79	84
Cropland/settlement	68	79	86	89
Woodland	32	58	72	79
Grassland	68	79	86	89
Bareland	77	86	91	94
Wetland	100	100	100	100
Water	100	100	100	100

5.2.7 Model Performance

Model performance was carried out to verify the robustness of the model to simulate hydrological processes. A model performance framework proposed by Moriasi *et al.* (2007) was used in this study. We used the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970), percent bias (PBIAS), and ratio of the root mean square to the standard deviation of measured data (RSR) as well as the R^2 for model evaluation. These methods are commonly used in judging model performance in many hydrological modeling studies (Moriasi *et al.*, 2007; Betrie *et al.*, 2011; Baker and Miller, 2013). Model simulation is judged as satisfactory if $NSE > 0.5$, $RSR \leq 0.70$ and PBIAS $\pm$ 25% (Moriasi *et al.*, 2007; Betrie *et al.*, 2011).

5.2.8 Evaluation of the streamflow response to changes in land use and land cover

To understand streamflow response to changes in land use and land cover in the watershed, three scenarios were used. The scenarios are defined based on the 1991, 2000 and 2015 land use and land cover maps as shown in Figure 5-2. Each of the LULC map was used as a land use input, while maintaining all the other input data including soil, DEM and climate data. The calibrated model was used to analyze the impact of changing land use on streamflow regime based on the land use maps of 1991, 2000 and 2015 using the same climatic data from January, 01, 1991 to December, 31, 2012. Changes in streamflow between the scenarios will indicate the influence of land use change. Similar approach was used successfully by Palamuleni *et al.* (2011) and Natkhin *et al.* (2015). Statistical and graphical comparisons were used to assess the simulated outputs. Peak flows simulated using the three land use scenarios were extracted from the flow duration curve using the a 5% exceedance probability (Q_5). Low flow duration was defined using the median flows of which a low flow day was defined as a day having flows less than the median flow (Q_{median}). Direct runoff which consists of surface runoff and fast lateral runoff was separated from the baseflow which is composed of the groundwater flow using the method suggested by Lim *et al.* (2010).

5.3 Results and Discussion

5.3.1 Land use/Land Cover (LULC) changes and LULC scenarios

The major land use types in the Upper Ruvu watershed are shown in Figure 5-2 and Table 5-4, indicate that the baseline year (1991) was dominated by forest and woodland land use types occupying 17% and 29%, respectively. However, in the ensuing 25 years the metrics changed and cropland and grassland became the major LULC occupying 29% and 20%, respectively (see Chapter 2). The unprecedented LULC changes in the watershed were mainly due to the conversion of natural forest and woodlands into cropland and grassland.

Table 5 - 4. Percentage area change of land use in the Upper Ruvu Watershed

Land use/Land Cover	1991	2000	2015
	% Cover	**% Cover**	**% Cover**
Natural Forest	17.2	10.2	3.9
Shrubland	15.2	18.4	21.0
Cropland	14.0	20.9	29.4
Woodland	28.9	24.3	16.1
Grassland	11.8	15.2	20.2
Bareland	2.4	2.4	3.8
Water	1.5	1.2	0.5
Wetland	8.9	7.3	4.4
Clouds and Shadows	17.2	0.2	0.9

5.3.2 Sensitivity Analysis

From the sensitivity analysis, parameters are ranked from the most sensitive to the least in Table 5-5. The most sensitive parameter is given a rank of 1 and the least sensitive out of the 20 parameters is given a rank of 20. The results show that the parameters that represent surface runoff, groundwater, soil properties, vegetation, channel and evaporation were more sensitive than others and therefore accurate estimation of these parameters is considered important for streamflow simulation with the SWAT model in the watershed. The symbols **r**, **v** and **a** before each parameter signifies multiplication of the value plus one to the default value, replacing the value with the default value and adding the value to the default value, respectively.

Table 5 - 5. Results of Calibration and Sensitivity Analysis

Rank	Parameter	Description
1	R__CN2.mgt	Curve Number (-)
2	V__RCHRG_DP.gw	Deep aquifer percolation fraction(-)
3	V__ALPHA_BNK.rte	Baseflow factor for bank storage ()
4	V__GW_DELAY.gw	Groundwater delay (days)
5	V__GW_REVAP.gw	Groundwater 'revap' coefficient (-)
6	R__SOL_AWC.sol	Soil layer Water Capacity (mm/mm)
7	R__HRU_SLP.hru	Average slope steepness (m/m)
8	V__REVAPMN.gw	Shallow Water Aquifer Threshold (mm)
9	V__LAT_TTIME.hru	Lateral flow travel (days
10	R__SLSUBBSN.hru	Average slope length (m)
11	V__ESCO.hru	Soil evaporation compensation factor(-)
12	V__CH_K2.rte	Hydraulic conductivity of the channel (mm/h)
13	R__SOL_BD.sol	Moist bulk density (g/m^3)
14	V__ALPHA_BF.gw	Baseflow alpha factor (days)
15	A__GWQMN.gw	Threshold of water in the shallow aquifer (mm H_2O)
16	V__CH_N2.rte	Channel manning's "n"
17	V__EPCO.hru	Plant uptake compensation factor (-)
18	R__SOL_K.sol	Saturated hydraulic conductivity (mm/hr)
19	V__SURLAG.bsn	Surface runoff lag coefficient (-)
20	V_OV_N.hru	Manning's n value (-)

The results showed that simulated streamflow is most sensitive to the SCS runoff curve number (CN2) parameter due to its significance in surface runoff prediction. Decreasing the CN2 values usually results in reduced surface runoff and increased infiltration, baseflow and groundwater recharge, and increasing the value results in increased surface runoff. The response of surface runoff to changes in CN2 values was manually tested by modifying values from its default value for each land use and hydrologic soil group combination to ±10% and ±15%. Results in Figure 5-4 show variation of surface runoff to the modification in CN2 values. Other parameters with high model sensitivity are related to groundwater, soil and channel properties. High sensitivity of streamflow prediction to CN2 has been reported in other studies (e.g., Mulungu and Munishi, 2007; Ndomba *et al.*, 2008; Birhanu, 2009) in Tanzania. Baker and Miller (2013), reported a non-linear change in runoff on a monthly and annual basis when CN was modified in Njoro River in Kenya.

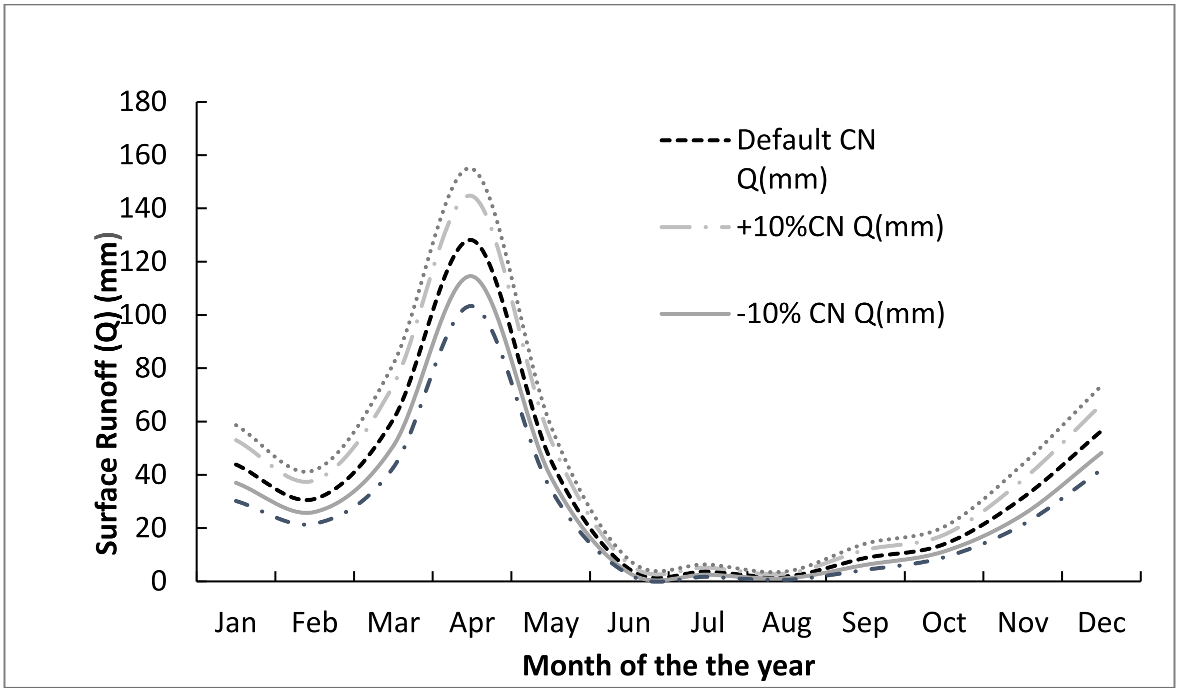

Figure 5 - 4. SWAT monthly surface runoff response to modification of CN values.

5.2.4 Model calibration and evaluation results

As SWAT consists of a large number of parameters, some of the parameters identified during the sensitivity analysis were not used in the calibration process to avoid over parameterization of the model. Following the guidelines by Moriasi *et al.* (2007) and Neitsch *et al.* (2002), 8 parameters were selected based on sensitivity analysis (Table 5-5) and used in the calibration process. The results of the calibration process showing the range of adjusted values and the fitted values are shown in Table 5-6. The model was calibrated at daily time step from January, 01, 1973 to December, 31, 1977 and evaluated from January, 01, 1978 to December, 31, 1982. Results of the calibration and evaluation processes at the two stations are presented in Figure 5-5 and Figure 5-6.

Table 5 - 6. Results of model calibration

Rank	Parameter	Range	Fitted value
1	R_CN2.mgt	-0.66 - 0.31	-0.17
2	V_RCHRG_DP.gw	-0.15 - 0.53	0.36
3	V__ALPHA_BNK.rte	0.25 – 0.33	0.28
4	V_GW_DELAY.gw	48.26 - 94.77	49.19
5	V_GW_REVAP.gw	0.02 – 0.2	0.18
6	R_SOL_AWC.sol	0.39 – 0.71	0.56
7	R__HRU_SLP.hru	-0.18 - -0.02	-0.03
8	V_REVAPMN.gw	-2.22 – 6.56	3.58

As shown in Figure 5-5, the model performed fairly well during both calibration and evaluation stages. The mean simulated streamflow at 1H5 was 17.0 m^3s^{-1} against measured streamflow of 15.48 m^3s^{-1}, while at 1H10 simulated mean streamflow was 50.4 m^3s^{-1} against measured streamflow of 45.8 m^3s^{-1}. The results show a good agreement between the simulated and the measured streamflow at both gauging stations as shown by the hydrographs in Figure 5-5 and Figure 5-6. From the hydrographs shown for the two outlets, it can be observed that despite the general agreement, the models overestimated baseflow by close to 45% in August, 1975 at 1H5. The disparities might have been contributed by the uncertainties in the input data and especially variables that are related to the calculation of evapotranspiration. Underestimation of the baseflow was observed in 1978 and in 1980 at 1H5. The model under-predicted peak flows in some years, and this is visible for November, 1973 and April 1974 for the 1H5 gauging station and May, 1974 and April, 1975 at 1H10 gauging station. This underscores the problem of input data, especially rainfall data. Observed streamflow data appeared to be exceptionally high from November, 1978 to the long rainy season of 1979 at both gauging stations. This was considered suspicious, and some data were therefore not included in the evaluation process. This was considered a reasonable approach in reducing uncertainty from the observed streamflow data during the evaluation. The approach was also reported by Baker and Miller (2013) who excluded a period of two years due to missing data of more than 100 days in each of the years.

With exceptions of these few cases, there was a general good agreement of simulated against measured data for both gauging stations. This was confirmed by reasonable NSE, PBIAS and RSR coefficients shown in Table 5-7 for both gauging stations.

Table 5 - 7. Calibration and Evaluation Results for streamflow for SWAT Model

Station	NSE		PBIAS		RSR	
	Calibration	Evaluation	Calibration	Evaluation	Calibration	Evaluation
1H5*	0.69	0.68	-7.8	17.3	0.56	0.57
1H10*	0.84	0.67	-9.9	-21.6	0.40	0.42

*1H5 – Ruvu at Kibungo Bridge, 1H10-Ruvu at Mikula.

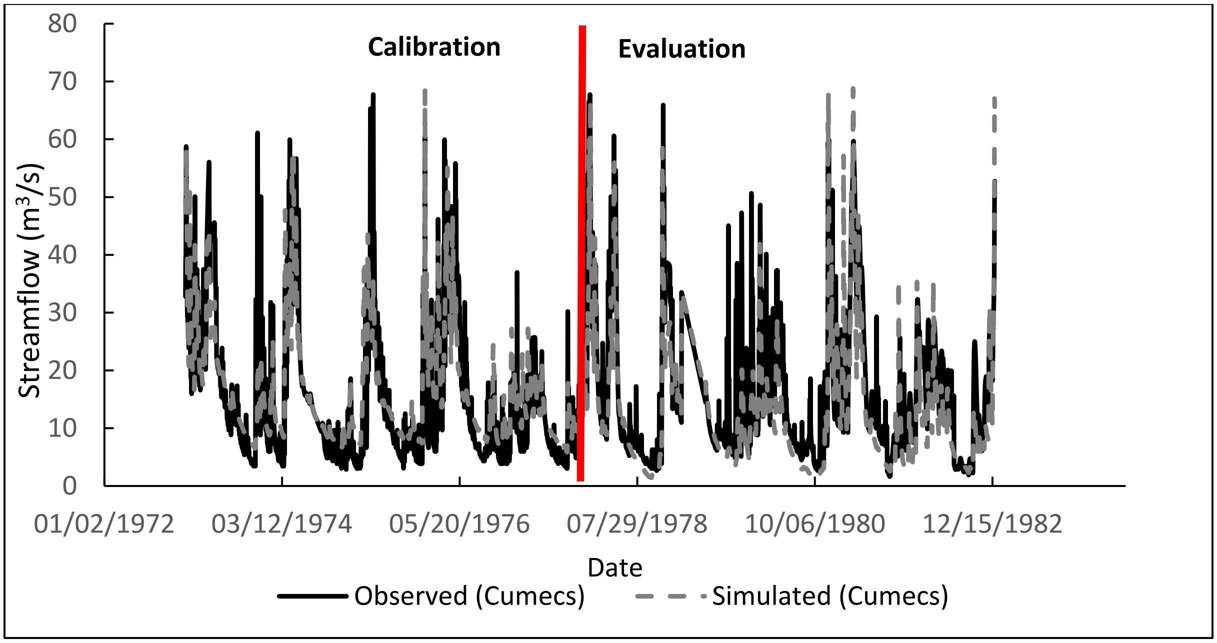

Figure 5 - 5. Comparison of daily hydrographs between the observed at the outlet of 1H5 Ruvu at Kibungo Bridge for calibration (1976-1980) and evaluation (1981- 1982)

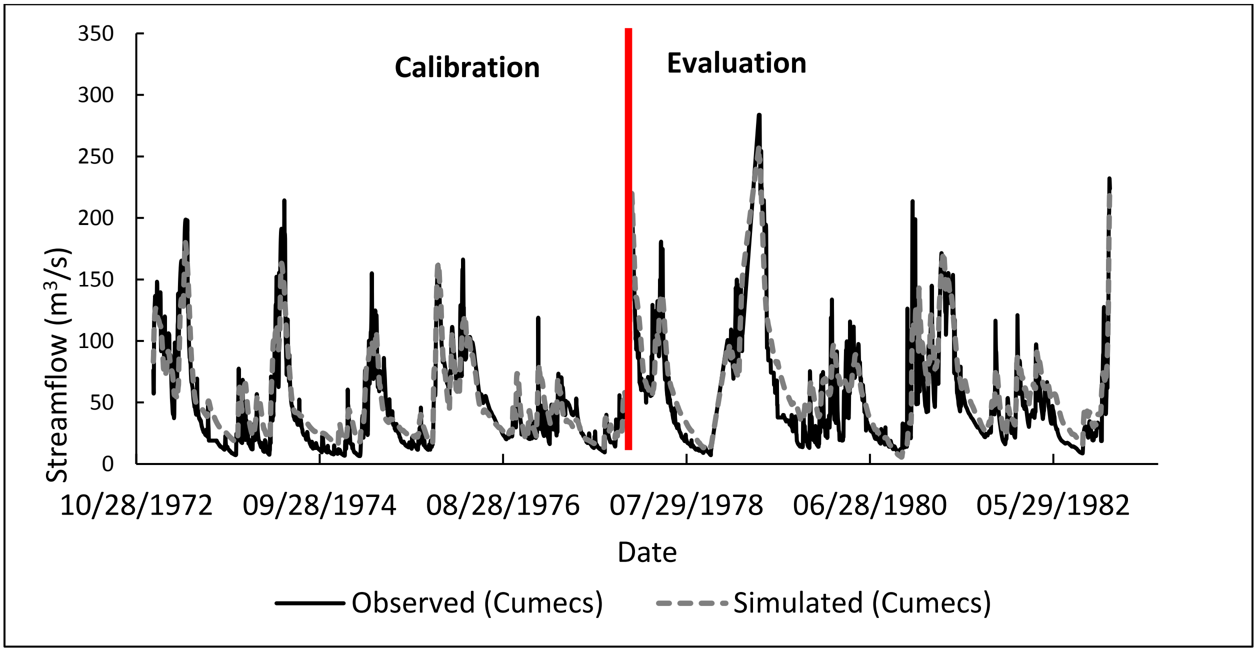

Figure 5 - 6. Comparison of daily hydrographs between the observed discharge at the outlet of 1H10 Ruvu at Mikula for calibration (1973-1977) and evaluation (1978- 1982)

Results from the calibration and evaluation of the model shown by time series plots, NSE, PBIAS, RSR and R^2 indicate that the calibrated model was able to represent the measured streamflow at a reasonable and acceptable level. The location of the outlet stations (one in the upstream and one in the downstream) help to represent the performance of the model in the two areas. The model was able to describe streamflow of the watershed satisfactorily well following the model performance indices suggested in Moriasi *et al.* (2007) and time series of hydrographs shown in Figure 5-5 and Figure 5-6. A scatter plot (Figure 5-7) between the measured and simulated streamflow values show a good correlation with a R^2 of 86% at 1H10 during calibration and evaluation process. The good NSE, PBIAS, RSR and R^2 results in both the calibration and evaluation stages suggest that the calibrated model can describe streamflow of the watershed and can therefore subsequently be used with confidence to investigate streamflow responses to changes in land use and land cover changes and other alterations in the Upper Ruvu watershed.

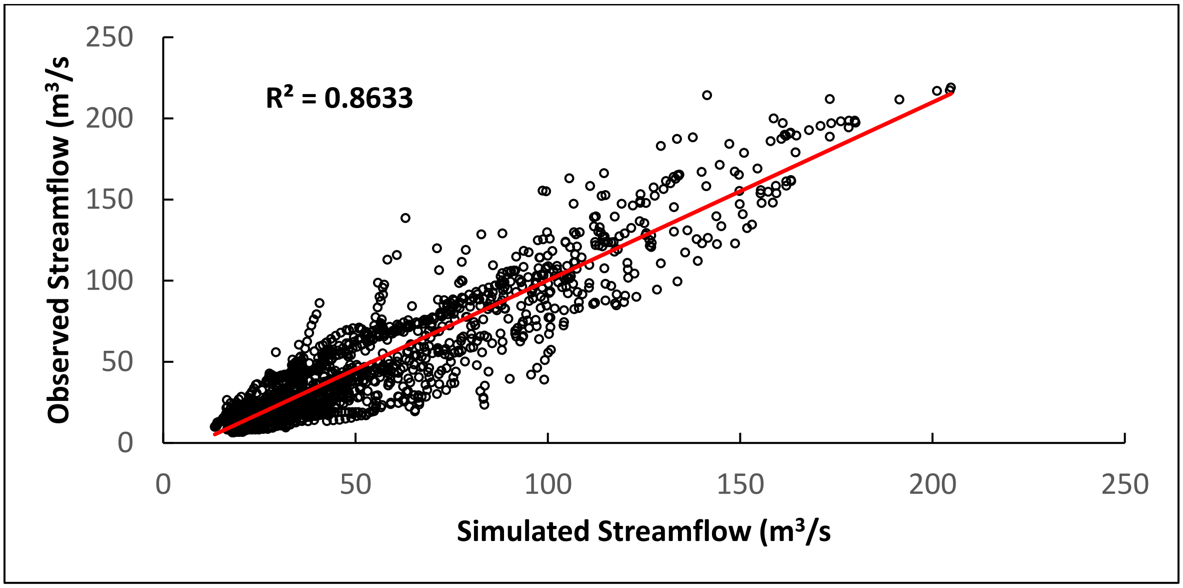

Figure 5 - 7. Scatter plot of measured streamflow against simulated flow for calibration at 1H10

5.3.5 Streamflow response to LULC change observed between 1991 and 2015.

The LULC of 1991, 2000 and 2015 were used as inputs to the model and were simulated to evaluate the response of streamflow due to the changes in land use and land cover in the watershed. Simulated results for the 1991 LULC map were compared with the observed streamflow for 1991 at Mikula (1H10). There was a good agreement between the observed streamflow and simulated streamflow for 1991, as shown by the scatter plot (Figure 5-7) with R^2 equal to 0.87 and NSE equal to 0.85. A comparison of monthly averages of simulated and observed streamflow for periods from 1991 to 2012 is shown in Figure 5-8(b).

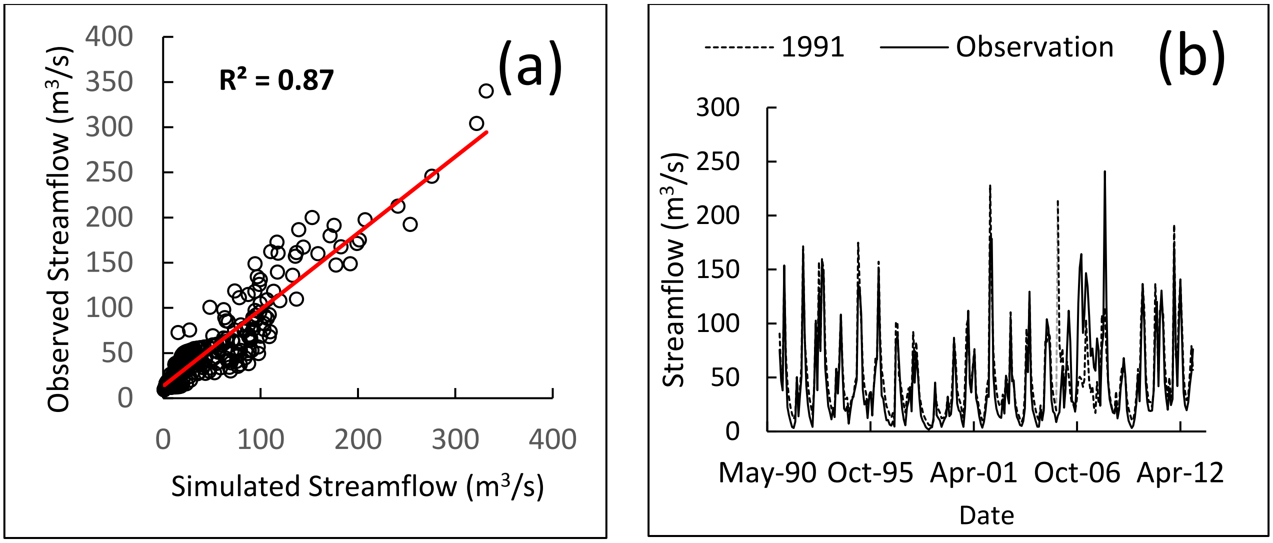

Figure 5 - 8. Scatter plot of measured against simulated stream flow at 1H10 (a) and comparison of average monthly observed and simulated streamflow at 1H10 (b).

A comparison of daily streamflow simulated using the three land cover maps for the three time periods simulated for 1991 are shown in Figure 5-9. The observed streamflow for 1991 compared well with the simulated streamflow using the 1991 LULC. The results indicate that there was a general increase of peak flows during the wet season and a decrease in baseflow during the dry season. It can be observed (Figure 5-9) that during the dry period in 1991, baseflow was lower for the simulated flows using the 2015 LULC than for the baseline period (which also appear to be in the same magnitude as the observed). The decrease in baseflow can also be observed the 2000 LULC scenario. In comparison with the baseline (1991 LULC), the mean daily streamflow simulated for the three LULC scenarios show that that the average daily streamflow at 1H10 decreased by 2% from 47.41 m^3s^{-1} in 1991 to 46.32 m^3s^{-1}. There was a decrease of approximately 12% from 47.41 m^3s^{-1} in 1991 to 41.50 m^3s^{-1} in 2015 (Table 5-8). Monthly streamflow averages shown in Figure 5-10 also confirm the suggestion that there was a general increase in peak flows and a decrease in baseflow as LULC changed from the baseline period to the current scenario (2015) as baseflow for the 2015 LULC scenario was consistently lower. The increase and decrease of streamflow using the same climate data as used in this study can be attributed to the change in land cover, especially as more forests were converted to agricultural lands.

Table 5 - 8. Effects of Changes in LULC on Q_5, $Q_{average}$ and Low Flow Duration for 1991, 2000 and 2015 LULC at 1H10 (Ruvu River at Mikula)

	1991 LULC	2000 LULC	Impact(1991-2000)	2015 LULC	Impact(1991-2015
Q_5 (m^3s^{-1})	128.85	151.6	5%	144.38	12%
$Q_{average}$ (m^3s^{-1})	47.41	46.32	-2%	41.50	-13%
Low Flow Duration (m^3s^{-1})	36.29	36.09	-0.5%	29.01	-25%

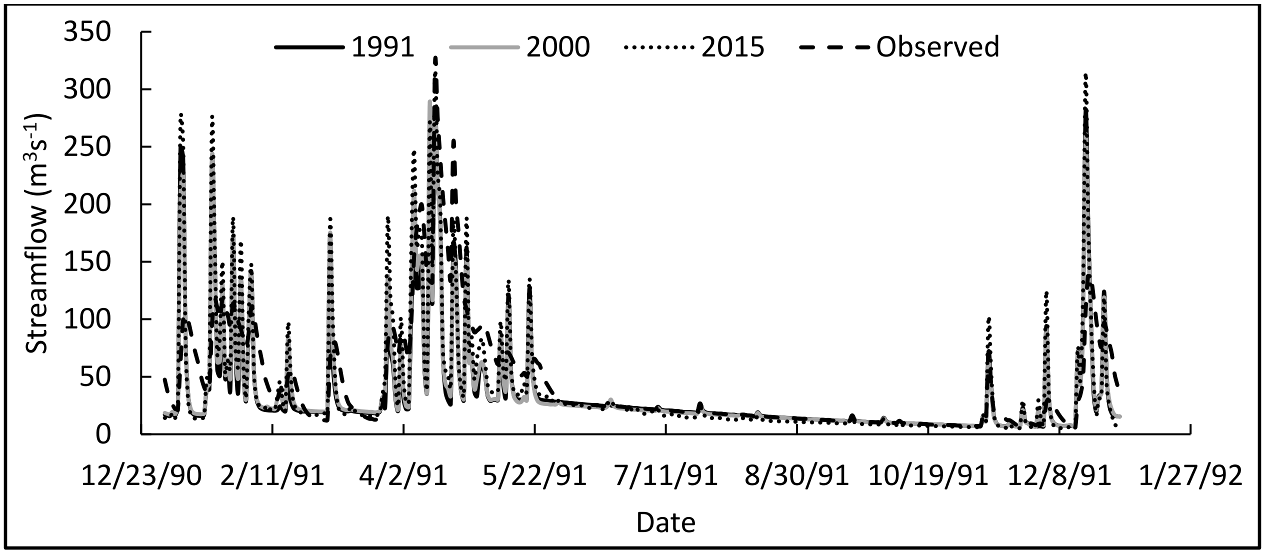

Figure 5 - 9. Time series of simulated and observed streamflow for 1991

Baseflow for the 2015 LULC scenario was consistently low in most of the years from 1991 to 2012. The decrease in areas covered with forest land use type in the upper parts of the watershed may cause a decline in interception and infiltration due to the loss of surface roughness, resulting in higher rainfall proportion being converted into surface runoff than is infiltrated into the soil for groundwater recharge. This could be linked to the presence of high peak flows which are directly taken as surface runoff in the rainy season and less baseflow available in the dry season. The observed decline of streamflow in recent years can mainly be attributed to the fact that only a small fraction of rainfall is taken for the infiltration during the wet season due to loss of surface cover. In a study in the Ngerengere River watershed in Tanzania, Natkhin *et al.* (2015), reported an increase of between 9-17% of high flows due to changes in land use. Baker and Miller (2013), reported an increase in surface runoff and a decrease in baseflow following changes in land cover especially in the upper part of River Njoro in Kenya. Legesse *et al.* (2003), reported a decrease of about 8% when the dominantly cultivated/grazing land would be converted to woodland. In a watershed in India, Babar and Ramesh (2015), reported a small change in streamflow, but increase in peak flows which occurred right at the month of high rainfall, despite a small (3.2%) change in forest cover between 2003 and 2013.

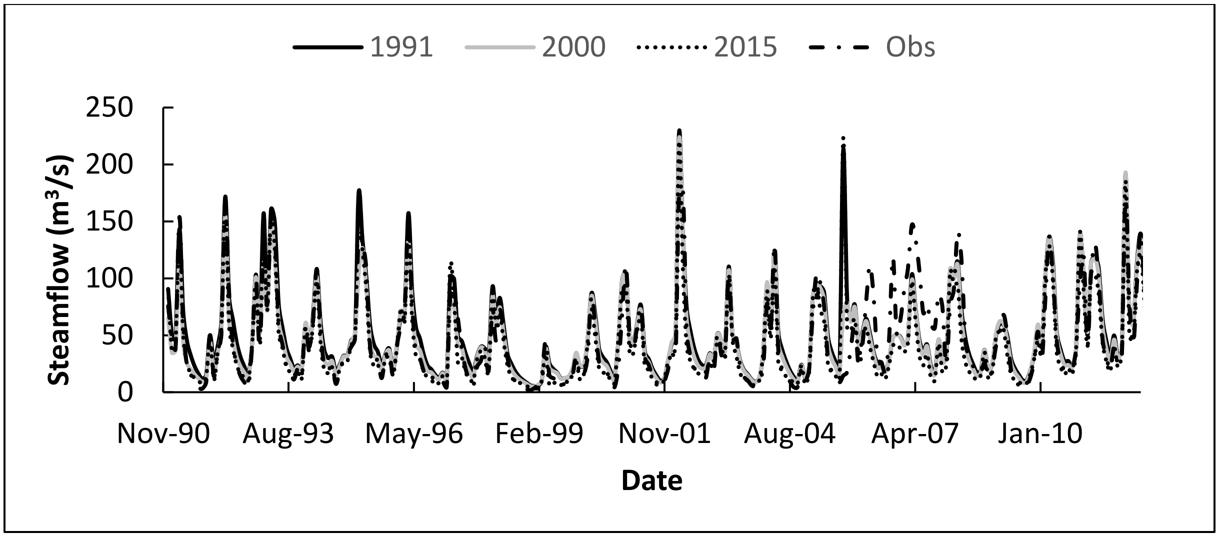

Figure 5 - 10. Average monthly streamflow: observed and simulated with LULC of 1991, 2000 and 2015.

Figure 5-11 shows the daily duration curves (FDC) of the three LULC scenarios in comparison with the observed. The results show that peak flows exhibited by the 5th percentile (Table 5-8) increased by 5% and 12% for 2000 and 2015, respectively from the baseline (1991) scenario.
The results show that in the study area, streamflow in the year 1991 to 2012 was at least 39 m^3s^{-1} 60% of the time for the 2015 LULC scenario and was at least 41 m^3s^{-1} 60% of the time for the baseline scenario. It is clear from the curves that baseflow was consistently lower for the year 2015, compared to the baseline year (1991). It can also be noted that the low flow duration which is shown decreased by 0.5% and 25%, respectively from the baseline scenario.

This can be confirmed by the steeper FDC towards the peak flows for the 2015 LULC scenario compared to the 2000 and the baseline scenario showing the influence of the land conversions on peak flows and its overall effect on the hydrological regime. These results show that as loss of forest cover continued to be realized in the watershed through the rapid increase of peak flows. Similar observations were reported by Natkhin *et al.* (2015) in the Mgude sub-watershed where change in peak flows due to land use change was about 17%. Other studies such as Ochoa-Tocachi *et al.* (2016), Palamuleni *et al.* (2011) and Githui *et al.* (2009) reported the influence of increase in cultivated areas on streamflow especially peak and low flows.

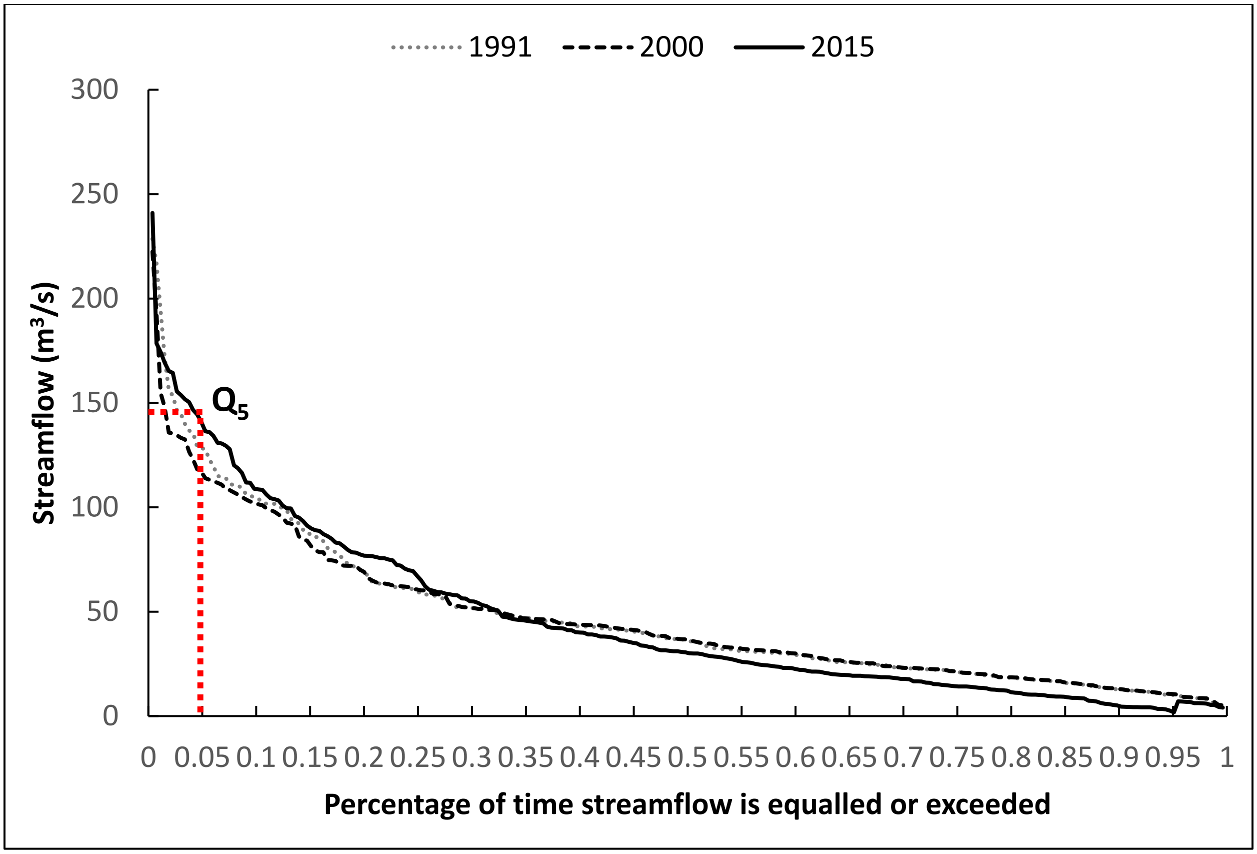

Figure 5 - 11. Average daily Flow duration curves for the period 1991 to 2012 at 1H10

Average monthly streamflow measured at the 1H10 gauging station for the hydrological year starting October is shown in Figure 5-12. The mean monthly average in the short rainy season reaches approximately 50 m^3s^{-1} in December and reaches approximately 121 m^3s^{-1} in April during the long rainy season and were high for the year 2015. The results confirm the assertion that peak flows have been increasing in the wet season from 1991 to 2015. The rising limb of the hydrograph occurs much faster for the year 2015 as compared to the 1991 and 2000 scenarios. It was further realized that there was an increase of approximately 7% of mean monthly streamflow in the long rainy season (March-May) in 2015 compared to the baseline, and there was no significant increase in 2000. On the other hand, a decrease of approximately 25% and 12% for June-September and January-February respectively for the 2015 LULC scenario compared to the baseline scenario. A decrease of between 1 to 3% of average monthly streamflow was observed in the dry season for the 2000 LULC scenario compared to the baseline scenario. In addition, an increase of approximately 2% was estimated for the March-May season in the year 2000 compared to the year 1991. From the results, it can be realized that the increase of streamflow in the rainy season were surpassed by the decrease in average monthly streamflow during the dry season resulting in the overall streamflow reduction. However, it is important to realize that monthly averages of streamflow may not provide a clear synopsis of the influence of peak flows in the wet season, mainly because surface runoff is dependent on rainfall which is unevenly distributed in a month and attenuation of the hydrograph at a monthly scale can be expected. In the absence of vegetation cover, most of the falling rain is converted directly into runoff due to less resistance and less infiltration, and may create undesirable impacts such as floods. The decrease in the baseflow during the dry season is a challenge in water resources management.

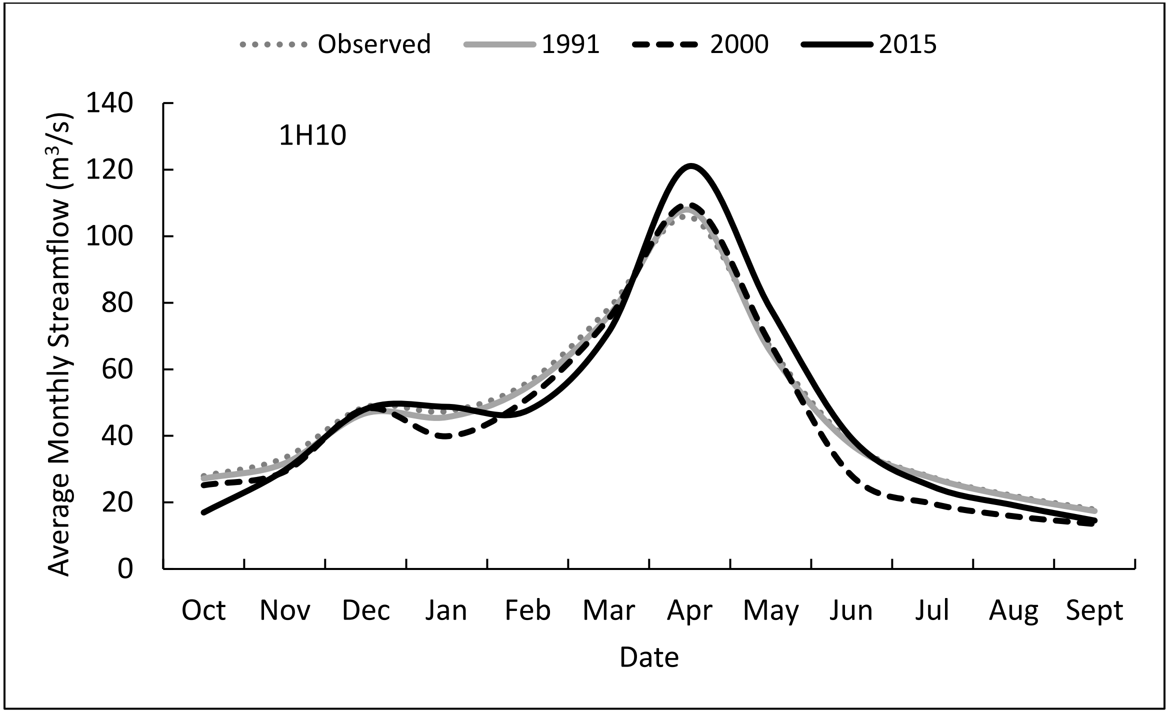

Figure 5 - 12. Average monthly streamflow for period between 1991 and 2012 at 1H0 gauging station

Basin-wide annual analysis of surface runoff and groundwater was done by comparing the simulated variables for each of the LULC scenario with values obtained from a JICA (2012) report. JICA (2012) reported about 229 mm and 48 mm of surface runoff (overland flow) and groundwater recharge, respectively. Noteworthy changes were observed in surface runoff and groundwater for 2000 and 2015, compared to the baseline land use. Figure 5-13 shows the impacts of LULC change on direct surface runoff, and groundwater flow. The results indicate that there was consistent increase in direct surface runoff from the baseline period to 2015. The results indicate that in comparison with the baseline scenario in 1991, annual surface runoff was 10 mm and 95.2 mm higher in 2000 and 2015, respectively. The change was about 8% and 75% for 2000 and 2015 respectively. The results appear to be correlated with the changes in LULC reported in Chapter 2. The increase in direct surface runoff may be attributed to the fact that in 2015, the size of exposed soil (cropland and bareland) was higher resulting in low infiltration and higher curve number compared to the baseline year 1991. In addition, average annual evapotranspiration increased mainly due to the increase in evaporation from the cultivated soils, bare soils and to some extent grassland. As shown in Table 5-9, the average annual evapotranspiration increased from 458.3 in 1991 to 724 mm in 2015, making a 58% increase.

The increase in direct runoff as a result of conversion of forest into cropland and other human activities have been reported by Baker and Miller (2013) for the Njoro river and Githui *et al.* (2009) in the Nzoia River in Kenya. The two studies attributed the increase in direct surface to the increase in cultivated areas at the expense of forest. Ghaffari *et al.* (2010) reported an increase of about 33% of surface runoff and a 22% decrease in the groundwater recharge increase in rain-fed agriculture and bareland in in Iran. Similar observations were also done by Khoi and Suetsugi (2014) in Iran. On the other hand, there was a general decline of baseflow from the baseline scenario in 1991. Baseflow decreased by 43% and 67% in 2000 and 2015, respectively from 1991. Other studies have reported various results on the decline of groundwater flow as a result of forest conversions and land alterations (Ghaffari *et al.*, 2010; Baker and Miller, 2013; Khoi and Suetsugi, 2014). Decline of groundwater flow in the study watershed can be attributed to less water infiltration due to loss of forests and continued exposure of soils that limit water holding capacity. Land transformations that are rampant in the fragile steep slopes and the shifting cultivation practices leave the soils exposed and therefore reduce the capacity of the watershed to store water and consequently affect the dry season flows.

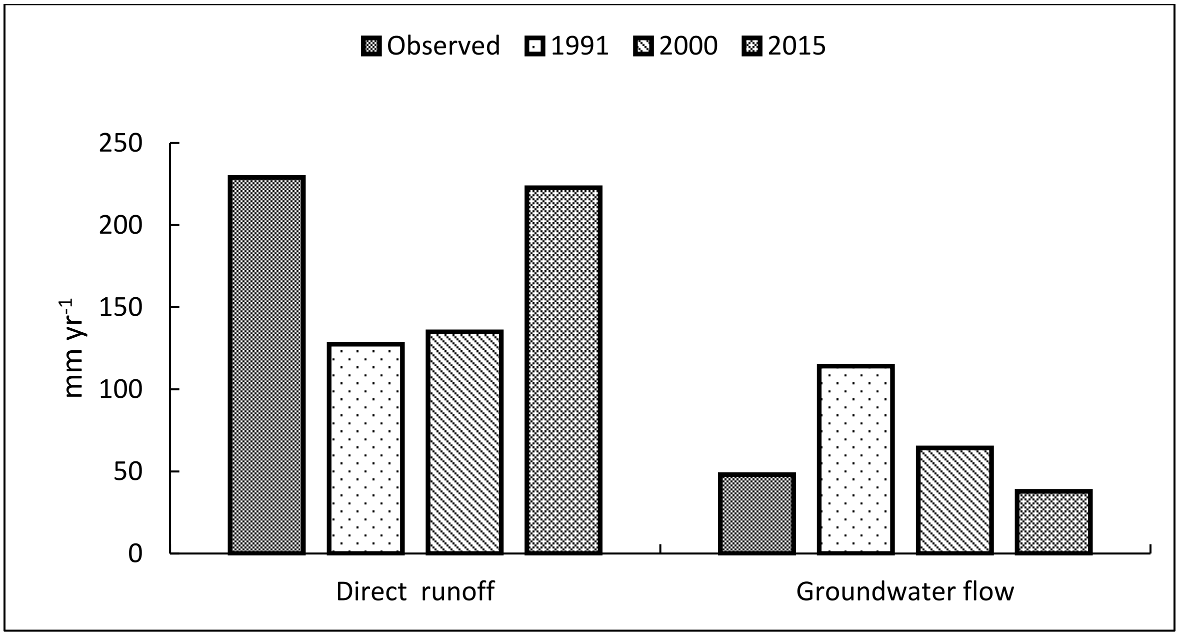

Figure 5 - 13. Annual hydrological response predictions for land use (1991, 2000, and 2015) in the Upper Ruvu watershed.

Table 5 - 9. Average annual basin-wide actual evapotranspiration and precipitation

Parameter	**1991**	**2000**	**2015**
Evapotranspiration (mm)	590.1	486.4	724.0
Precipitation (mm)	794.9	814.0	1255.0

5.3.6 Impacts of LULC changes on hydrology at the sub-watershed scale.

Results in Figure 5-14 show surface runoff from the different sub-watersheds for 1991 and 2015, respectively. These results indicate that the contribution of surface runoff was highly variable. Surface runoff is generated from the sub-watersheds located in the uplands and mostly where human activities are dominant. The results further show that more surface runoff (>169 mm) was generated in sub-watersheds in the uplands. These are areas around Kiroka, Mkuyuni, and other populated areas. Other areas where surface runoff was generated in high amounts include Kibungo and its upstream areas such as Mbezi, as well as areas around Mvuha and Mgeta sub-watersheds. The western parts are dominated by woodland, which have not experienced a significant change in runoff between 1991 and 2015.

These results highlight the fact that increases in surface runoff contribution to streamflow is a result of conversion of natural landscapes (forest and woodland) to agriculture, bareland and grassland. Cropland and rural settlement expanded in the uplands in sub-watersheds 1 to 7, 15 and 17. Other areas that had experienced expansion of cropland include sub-watershed 26, 27, and 29 up to 34. It can be observed that, the number of sub-watershed which experienced surface runoff greater than 169 mm increased from 12 to 18 between 1991 and 2015. The increase in surface runoff in the upstream basins such as Kiroka, Kinole, Kibungo Juu, Mvuha, Mfizigo, and Mbezi appear to be consistent with the changes in land use and land cover. As these areas are characterized by high rainfall amounts, the increase in surface runoff suggests that a higher percentage of rainfall is converted into runoff than is infiltrated into the soil for groundwater recharge. These results suggests that the changes in LULC from the baseline cover in 1991 to 2015 in the upstream sub-watersheds may have impacts on the downstream parts of the watershed.

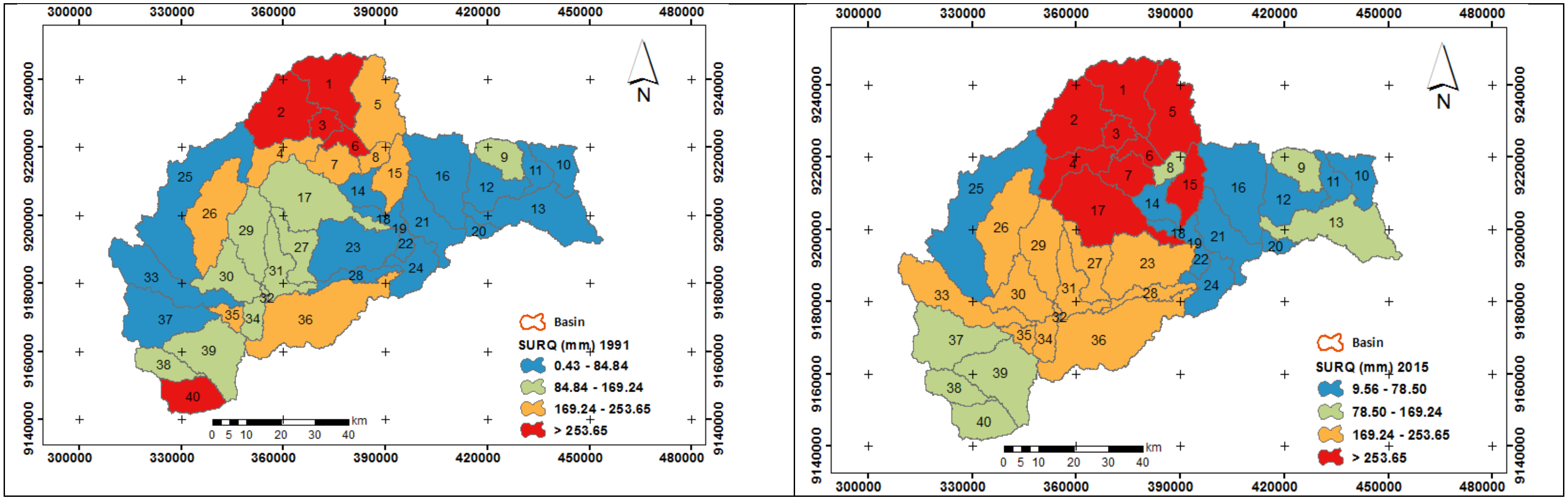

Figure 5 - 14. Spatial distribution predicted annual surface runoff (SURQ) (mm) for the simulated period 1991-2012 for land use conditions of 2015.

5.4 Conclusions

Lack of appropriate and reliable data is a major constraint in deriving information that help in developing strategies for sustainable water resources management at the landscape and watershed scale. This study was designed to investigate the effects of changes in land use and land cover on streamflow over a 25 year period (1991-2015) in a data scarce watershed, the Upper Ruvu watershed in Tanzania. The SWAT model using its ArcGIS interface was applied to the watershed and sensitivity analysis, model calibration, and evaluation were carried out to evaluate model performance in the simulation of streamflow. The results indicate a reasonable model performance based on goodness of fit and statistical comparisons suggesting that SWAT can be used for assessing impacts of land use and land cover change in the Upper Ruvu watershed. The SWAT model was considered as a suitable approach, although mostly was limited by rainfall data.

The model has shown that a change in land use and land cover from the baseline scenario (1991) showed a slight decrease of 2% in average streamflow by 2000 (46.32 m^3s^{-1}), but a decrease of up to 13% of average streamflow by 2015 (41.50 m^3s^{-1}) from the baseline period (47.41 m^3s^{-1}) Forest made up approximately 17% of the total watershed area in 1991, but was only 4% of the watershed area by 2015. On the other hand cropland increased from 14% in 1991 to approximately 30% in 2015. The increase in percentage area occupied by cropland and the decrease of percentage area occupied by forest and woodland showed a clear influence on streamflow in the watershed. Average peak flows (Q_5) increased by 5% and 12% for 2000 and 2015, respectively from the baseline period. Moreover, peak flows increased by 7% in the long rainy season (March-May) and baseflow decreased by 12% (January and February) and 25% (June through September) in the dry season. These results suggest the influence of changes in land use and land cover on hydrological components, which ultimately have significant. Changes in LULC in the watershed have significant effect on surface runoff generation as 8% and 75% increase in surface runoff was estimated for 2000 and 2015, respectively from the baseline scenario in 1991. The increase in surface runoff specifically in the wet season, suggest less is taken for infiltration and may translate into scarcity of soil water availability for plants and for baseflow contribution. This may have implications on smallholder farmers and different water users from various sectors.

Specifically, this study has quantified changes in hydrological components in the upper Ruvu watershed following the LULC changes for the 25 year period between 1991 and 2015. The study has shown that the change in land use from natural areas to cropland and grassland areas leads to an increase in the peak flows which have an implication in the magnitude of floods. The change in land use had also caused a decrease in low-flow duration. The results highlight the areas of significant changes and provides spatial based quantitative information that will help water managers and decision makers in making informed choice for sustainable land and water resources planning and management. The approach used in this study can potentially be used in other watersheds for assessing hydrologic response to changes in land use as well as climate change, provided that digital land cover and climate information is available. Future studies can include investigations of different land use scenarios based on envisioned changes in the watershed, and climate change scenarios. Impacts of land restoration can also be investigated by developing scenarios with potential benefits for the ecosystems and the hydrology.

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References

Abbaspour K, Vejdani M, Haghighat S. 2007. SWAT-CUP calibration and uncertainty programs for SWAT. In: MODSIM 2007 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand.

Abbaspour KC, Faramarzi M, Ghasemi SS, Yang H. 2009. Assessing the impact of climate change on water resources in Iran. Water Resources Research, **45**. DOI: Artn W10434

Doi 10.1029/2008wr007615.

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, **300**: D05109.

Arnold J, Moriasi D, Gassman P, Abbaspour K, White M, Srinivasan R, Santhi C, Harmel R, Van Griensven A, Van Liew M. 2012. SWAT: Model use, calibration, and validation. Transactions of the ASABE, **55**: 1491-1508.

Arnold JG, Fohrer N. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modelling. Hydrological Processes, **19**: 563-572. DOI: 10.1002/hyp.5611.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large area hydrologic modeling and assessment part I: Model development1. Wiley Online Library.

Babar S, Ramesh H. 2015. Streamflow Response to Land Use–Land Cover Change over the Nethravathi River Basin, India. Journal of Hydrologic Engineering, **20**: 05015002.

Baker TJ, Miller SN. 2013. Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed. Journal of Hydrology, **486**: 100-111. DOI: http://dx.doi.org/10.1016/j.jhydrol.2013.01.041.

Batjes NH. 2004. SOTER-based soil parameter estimates for Southern Africa. Wageningen: ISRIC-World Soil Information.

Betrie G, Mohamed Y, Griensven Av, Srinivasan R. 2011. Sediment management modelling in the Blue Nile Basin using SWAT model. Hydrology and Earth System Sciences, **15**: 807-818.

Biftu GF, Gan TY. 2001. Semi-distributed, physically based, hydrologic modeling of the Paddle River Basin, Alberta, using remotely sensed data. Journal of Hydrology, **244**: 137-156. DOI: 10.1016/S0022-1694(01)00333-X.

Birhanu BZ. 2009. Hydrological modeling of the Kihansi river catchment in South Central Tanzania using SWAT model. International Journal of Water Resources and Environmental Engineering, **1**: 001-010.

Bondelid TR, McCuen RH, Jackson TJ. 1982. Sensitivity of SCS Models to Curve Number Variation1. Wiley Online Library.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, **55**: 3-23. DOI: http://dx.doi.org/10.1016/0022-1694(82)90117-2.

Breuer L, Huisman J, Willems P, Bormann H, Bronstert A, Croke B, Frede H-G, Gräff T, Hubrechts L, Jakeman A. 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. Advances in water resources, **32**: 129-146.

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology, **310**: 28-61. DOI: http://dx.doi.org/10.1016/j.jhydrol.2004.12.010.

Burgess N, Doggart N, Lovett JC. 2002. The Uluguru Mountains of eastern Tanzania: the effect of forest loss on biodiversity. Oryx, **36**: 140-152.

Cai T, Li Q, Yu M, Lu G, Cheng L, Wei X. 2012. Investigation into the impacts of land-use change on sediment yield characteristics in the upper Huaihe River basin, China. Physics and Chemistry of the Earth, Parts A/B/C, **53–54**: 1-9. DOI: http://dx.doi.org/10.1016/j.pce.2011.08.023.

Calder IR, Hall RL, Bastable HG, Gunston HM, Shela O, Chirwa A, Kafundu R. 1995. The Impact of Land-Use Change on Water-Resources in Sub-Saharan Africa - a Modeling Study of Lake Malawi. Journal of Hydrology, **170**: 123-135.

Carpenter SR, Fisher SG, Grimm NB, Kitchell JF. 1992. Global change and freshwater ecosystems. Annual Review of Ecology and Systematics: 119-139.

Chaplot V, Darboux F, Bourennane H, Leguédois S, Silvera N, Phachomphon K. 2006. Accuracy of interpolation techniques for the derivation of digital elevation models in relation to landform types and data density. Geomorphology, **77**: 126-141.

Costa MH, Botta A, Cardille JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, **283**: 206-217.

Cronshey R. 1986. Urban hydrology for small watersheds. US Dept. of Agriculture, Soil Conservation Service, Engineering Division.

Dagg M, Blackie JR. 1965. STUDIES OF THE EFFECTS OF CHANGES IN LAND USE ON THE HYDROLOGICAL CYCLE IN EAST AFRICA BY MEANS OF EXPERIMENTAL CATCHMENT AREAS. International Association of Scientific Hydrology. Bulletin, **10**: 63-75. DOI: 10.1080/02626666509493424.

De Pauw E. 1984. Soils, physiography and agroecological zones of Tanzania. Ministry of Agriculture, Dar-es-Salaam, Tanzania/FAO, Rome.

Edwards K, Blackie J. 1981. Results of the East African catchment experiments 1958-1974. Tropical agricultural hydrology: 163-188.

Eshleman KN. 2013. Hydrological Consequences of Land Use Change: A Review of the State-of-Science. In: Ecosystems and Land Use Change, American Geophysical Union, pp: 13-29.

Faramarzi M, Abbaspour KC, Schulin R, Yang H. 2009. Modelling blue and green water resources availability in Iran. Hydrological Processes, **23**: 486-501. DOI: Doi 10.1002/Hyp.7160.

Fohrer N, Haverkamp S, Eckhardt K, Frede H-G. 2001. Hydrologic response to land use changes on the catchment scale. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, **26**: 577-582.

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK. 2005. Global consequences of land use. science, **309**: 570-574.

Ghaffari G, Keesstra S, Ghodousi J, Ahmadi H. 2010. SWAT-simulated hydrological impact of land-use change in the Zanjanrood Basin, Northwest Iran. Hydrological processes, **24**: 892-903.

Githui F, Mutua F, Bauwens W. 2009. Estimating the impacts of land-cover change on runoff using the soil and water assessment tool (SWAT): case study of Nzoia catchment, Kenya/Estimation des impacts du changement d'occupation du sol sur l'écoulement à l'aide de SWAT: étude du cas du bassin de Nzoia, Kenya. Hydrological sciences journal, **54**: 899-908.

Hargreaves G, Samani Z. 1985. Reference Crop Evapotranspiration from Temperature. Applied engineering in agriculture.

Hibbert AR. 1965. Forest treatment effects on water yield. Citeseer.

Hornbeck JW, Adams MB, Corbett ES, Verry ES, Lynch JA. 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology, **150**: 323-344. DOI: http://dx.doi.org/10.1016/0022-1694(93)90115-P.

IUCN. 2010. IUCN Eastern and Southern Africa Programme, 2010. The Ruvu Basin: A Situation Analysis., xvi + 96 pp. IUCN - ESARO Publications Service Unit

JICA. 2012. The Study on Water Resources Management and Development in Wami/Ruvu Basin in the United Republic of Tanzania. Ministry of Water (MoW).

Khoi DN, Suetsugi T. 2014. The responses of hydrological processes and sediment yield to land-use and climate change in the Be River Catchment, Vietnam. Hydrological Processes, **28**: 640-652. DOI: 10.1002/hyp.9620.

Legesse D, Vallet-Coulomb C, Gasse F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. Journal of Hydrology, **275**: 67-85.

Lenhart T, Eckhardt K, Fohrer N, Frede H-G. 2002. Comparison of two different approaches of sensitivity analysis. Physics and Chemistry of the Earth, Parts A/B/C, **27**: 645-654.

Lim KJ, Park YS, Kim J, Shin Y-C, Kim NW, Kim SJ, Jeon J-H, Engel BA. 2010. Development of genetic algorithm-based optimization module in WHAT system for hydrograph analysis and model application. Comput Geosci-Uk, **36**: 936-944.

Ma Z, Kang S, Zhang L, Tong L, Su X. 2008. Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China. Journal of Hydrology, **352**: 239-249.

Mango LM, Melesse AM, McClain ME, Gann D, Setegen S. 2010. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management.

Monteith JL. 1965. Evaporation and environment. Symposia of the Society for Experimental Biology, **19**: 205.

Moriasi D, Arnold J, Van Liew M, Bingner R, Harmel R, Veith T. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. Asabe, **50**: 885-900.

Msaghaa JJ, Melesse AM, Ndomba PM. 2014. Modeling Sediment Dynamics: Effect of Land Use, Topography, and Land Management in the Wami-Ruvu Basin, Tanzania. In: Nile River Basin, Springer, pp: 165-192.

Mueller EN, Francke T, Batalla RJ, Bronstert A. 2009. Modelling the effects of land-use change on runoff and sediment yield for a meso-scale catchment in the Southern Pyrenees. Catena, **79**: 288-296. DOI: 10.1016/j.catena.2009.06.007.

Mulungu DM, Munishi SE. 2007. Simiyu River catchment parameterization using SWAT model. Physics and Chemistry of the Earth, Parts A/B/C, **32**: 1032-1039.

Nash J, Sutcliffe J. 1970. River flow forecasting through conceptual models part I—A discussion of principles. Journal of hydrology, **10**: 282-290.

Natkhin M, Dannowski R, Dietrich O, Steidl J, Lischeid G. 2014. Model-Based Impact Analysis of Climate and Land Use Changes on the Landscape Water Balance. In: Novel Measurement and Assessment Tools for Monitoring and Management of Land and Water Resources in

Agricultural Landscapes of Central Asia, Mueller L, Saparov A, Lischeid G (eds.) Springer International Publishing, pp: 577-590.

Natkhin M, Dietrich O, Schäfer MP, Lischeid G. 2015. The effects of climate and changing land use on the discharge regime of a small catchment in Tanzania. Regional Environmental Change, **15**: 1269-1280.

Ndomba P, Mtalo F, Killingtveit A. 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. Physics and Chemistry of the Earth, Parts A/B/C, **33**: 626-632.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR, King KW. 2002. Soil and Water Assessment Tool Theoretical Documentation. USDA-ARS Publication GSWRL 02-01 BRC 02-05 TR-01. USDA-ARS Publication.

Nietsch S, Arnold J, Kiniry J, Williams J. 2001. SWAT: Soil and water assessment tool user’s manual. Temple, TX: USDA Agricultural Research Service.

Ochoa-Tocachi BF, Buytaert W, De Bièvre B, Célleri R, Crespo P, Villacís M, Llerena CA, Acosta L, Villazón M, Guallpa M. 2016. Impacts of land use on the hydrological response of tropical Andean catchments. Hydrological Processes.

Palamuleni LG, Ndomba PM, Annegarn HJ. 2011. Evaluating land cover change and its impact on hydrological regime in Upper Shire river catchment, Malawi. Regional Environmental Change, **11**: 845-855.

Priestley CHB, Taylor RJ. 1972. On assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review, Vol 100, No 2, P 81-92, February 1972.

Rawls WJ, Ahuja LR, Brakensiek DL, Shirmohammadi A, Maidment D. 1992. Infiltration and soil water movement. McGraw-Hill Inc.

Schuol J, Abbaspour KC, Yang H, Srinivasan R, Zehnder AJ. 2008. Modeling blue and green water availability in Africa. Water Resources Research, **44**.

Tang Z, Engel B, Pijanowski B, Lim K. 2005. Forecasting land use change and its environmental impact at a watershed scale. Journal of environmental management, **76**: 35-45.

Tomer MD, Schilling KE. 2009. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. Journal of Hydrology, **376**: 24-33. DOI: http://dx.doi.org/10.1016/j.jhydrol.2009.07.029.

Tripathi M, Panda R, Raghuwanshi N. 2005. Development of effective management plan for critical subwatersheds using SWAT model. Hydrological processes, **19**: 809-826.

URT. 2011. United Republic of Tanzania (2011). Morogoro District Profile, Prime Minister’s Office: Ministry of Regional Administration and Local Government, Morogoro, Tanzania.

USDA. 1986. Urban hydrology for small watersheds. Technical release, no 55 (TR-55). US Dept. of Agriculture, Soil Conservation Service, Engineering Division.

Van Griensven A, Meixner T, Grunwald S, Bishop T, Diluzio M, Srinivasan R. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. Journal of hydrology, **324**: 10-23.

Veldkamp A, Lambin EF. 2001. Predicting land-use change. Agriculture, ecosystems & environment, **85**: 1-6.

WRBWO. 2008. Wami /Ruvu Basin Water Office (WRBWO). 2008. Business Plan.

Yanda P, Munishi P. 2007. Hydrologic and Land Use/Cover Change Analysis for the Ruvu River (Uluguru) and Sigi River (East Usambara) Watersheds. For WWF/CARE Dar es Salaam, Tanzania.

Yang Q, Tian H, Friedrichs MAM, Liu M, Li X, Yang J. 2015. Hydrological Responses to Climate and Land-Use Changes along the North American East Coast: A 110-Year Historical Reconstruction. JAWRA Journal of the American Water Resources Association, **51**: 47-67. DOI: 10.1111/jawr.12232.

Zhao Y, Zhang K, Fu Y, Zhang H. 2012. Examining Land-Use/Land-Cover Change in the Lake Dianchi Watershed of the Yunnan-Guizhou Plateau of Southwest China with Remote Sensing and GIS Techniques: 1974–2008. International journal of environmental research and public health, **9**: 3843-3865.

Chapter 6 Summary and Recommendations

Changes in hydrological regimes as a result of complex interactions of land use and cover, land management, and climate variability combined with increasing and competing demands for water, make management of water resources at watershed scale an extremely challenging task for hydrologists and water managers. Changes in land use and land cover and climate induced variability are strong drivers of changes in water quantity and quality of watersheds. While high rainfall events such as heavy rainstorms in the rainy season might result into soil erosion and flooding, decreases of river flows to no flow in the dry season, land alterations especially deforestation and increase in agricultural lands and impervious surfaces affect hydrological regimes at different scales. More often than not, changes in the quantity, timing, intensity or duration of rainfall, combined with changes in evapotranspiration due to higher temperatures lead to observed stream flow reduction.

Furthermore, factors affecting hydrological processes are interrelated and complex, therefore determining the causes of these changes, identifying, quantifying and predicting the consequences of land use change and climate variability have been major challenges for current and future hydrological research (Sivapalan *et al.*, 2003; DeFries and Eshleman, 2004; Ott and Uhlenbrook, 2004; Eshleman, 2013). The challenge is even bigger in watersheds in developing countries because of short lengths of most hydrological records, high natural variability of hydrological systems, paucity of detailed hydrometric measurements and small number of controlled small-scale experimental studies (DeFries and Eshleman, 2004; Eshleman, 2013) that limit the possibility of extrapolating results to other systems. Despite the importance for human and ecosystems sustainability, hydrological processes in watersheds amid changes in land use and cover and climate variability/change are still not well understood. It is crucial to understand the hydrological responses to these changes if we are to plan for sustainable ecosystems and the environment. Hydrologists and researchers are called upon to understand the consequences of changes on hydrological processes at different scales from plot, hillslope to watershed. This information is crucial for planning and water resources management and the need to quantify the extent to which land use and climate influence the hydrological conditions is deemed necessary for that purpose. The information could yield valuable insights into the spatial distribution of the process that control runoff and soil erosion generation and water quality in headwater and watersheds.

This study was focused on understanding the hydrological responses to changes in land use and land cover and variability in climate at different scales in a watershed characterized with complex terrains, highly variable climate and increased anthropogenic activities. In addressing the research questions, different approaches including use of remote sensing, plot experiments using rainfall simulators, experimental watersheds monitoring, statistical analysis of long term data of climate and streamflow and modeling using both empirical and physically based were employed. First, the study employed remote sensing and GIS using Landsat imagery to identify major land cover classes dominant in the area. We were able to identify eight land cover classes; natural forests, shrubland, cropland and rural settlement, woodland, grassland, bareland, wetlands and water. In a 25-year period between 1991 and 2015 significant land use and land cover changes were revealed, indicating huge losses of forests and woodlands and increases in agricultural lands followed by grasslands. The changes in land use and land covers had resulted in the increase in soil erosion and most soil losses were recorded from agricultural lands and least amounts were recorded from forests.

Second, in order to correlate the role of human activities and climate on the hydrology at headwater watersheds and at watershed scale, we initiated a two-year monitoring of streamflow, suspended sediments and climate variables in three headwater watersheds with different levels of degradation. We identified levels of disturbances through the percentage forest and agricultural land cover. Our hypothesis in this study was that the three headwater watersheds being located in a similar environment would exhibit homogeneous climate and hence the differences in streamflows and suspended sediments will entirely be attributed to human activities in the form of disturbances. We found significant differences in sediment yield in the three watersheds even when the rainfall patterns were not significantly different and baseflow contribution to flow was higher in the less degraded watershed than in the degraded watersheds. At the watershed scale, long term records of rainfall, evapotranspiration and streamflow revealed existence of trends exhibiting increasing and decreasing changes across time, but with more decreasing trends in rainfall and streamflow, but increasing trends in evapotranspiration. Human activities were found to contribute to about 54% of the changes in streamflow, compared to 46% of climate.

Third, we estimated the surface runoff, sediment yield and curve number from three land use types at plot scale using rainfall simulators. The use of rainfall simulators was intended to present a cost-effective measure of obtaining information from challenging environments with little use of resources within a short time. Results showed that croplands and the management of upland rice were responsible for majority of the runoff and sediment generation in the landscape. We also found that the presence of ground cover and some soil properties were the most influencing factors in runoff and sediment generation.

Fourth, we evaluated the SWAT model for applicability in tropical watersheds characterized with data scarcity. We found that the model performed satisfactorily well and was able to simulate streamflow at HRU, sub-watershed and watershed scale in comparison with measured data. We used the calibrated model to investigate streamflow responses to changes in land use and land cover for different periods using the developed land cover maps for 1991, 2000 and 2015. The results indicate that streamflow decreased by approximately 16% by 2015 from the baseline in 1991. Surface runoff increased as a result of increase in cultivated areas and loss of forests, and a decrease of groundwater due to loss of vegetation cover was recorded.

This study quantified for the first time in the watershed the hydrological responses of changes in different land uses and land cover on runoff, sediments and soil erosion, and the contribution of both climate and human activities on the changes in hydrology. We were able to identify hotspot areas of soil erosion and runoff in the watersheds, and vulnerability of different landscapes.

These results are important for water resources planning and management in the watershed, as hotspot areas for runoff and soil erosion can be used as starting point for landscape restoration as well as soil and water conservation in the watershed.

While this study was able to identify the variability of climate and their implications on hydrology, the responses of changes in future climate are uncertain, we therefore recommend future studies to focus on investigating the hydrological responses to projected future climate. This knowledge is important for resource sustainability as many projects are long term, and it may be unwise to realize in the future that planning did not consider the changes within the system. Depending on the future plans for land use, and in collaboration with water managers and policy makers, scenarios of change could be devised and tested in the SWAT model.

We propose additional plot scale experiments for different land cover types and different environments, as well as land management, as we have come to realize that land management plays a great role in the generation and transport of runoff and sediments from landscapes. The use of different rainfall intensity is crucial as variability in intensity and duration of natural rainfall are common. Combination of experiments using natural rainfall might give insights on the hydrological processes.

We propose extra efforts in data collection of both climatic and hydrological data as we have found from this study that data quality is an integral part of the success in building a sound model. Monitoring of sediments should also be emphasized and further, sediment modeling using SWAT would be appropriate if good quality data are available.

References

Sivapalan M, Takeuchi K, Franks SW, Gupta VK, Karambiri H, Lakshmi V, Liang X, McDonnell JJ, Mendiondo EM, O'Connell PE, Oki T, Pomeroy JW, Schertzer D, Uhlenbrook S, Zehe E. 2003. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. Hydrological Sciences Journal, **48**: 857-880. DOI: 10.1623/hysj.48.6.857.51421.

DeFries R, Eshleman KN. 2004. Land-use change and hydrologic processes: a major focus for the future. Hydrological Processes, **18**: 2183-2186. DOI: 10.1002/hyp.5584.

Ott B, Uhlenbrook S. 2004. Quantifying the impact of land-use changes at the event and seasonal time scale using a process-oriented catchment model. Hydrology and Earth System Sciences Discussions, **8**: 62-78.

Eshleman KN. 2013. Hydrological Consequences of Land Use Change: A Review of the State-of-Science. In: Ecosystems and Land Use Change, American Geophysical Union, pp: 13-29.

Appendix A Supplementary materials and data

Figure A - 1 Flow Chart showing the main processes for soil Erosion modeling using RUSLE

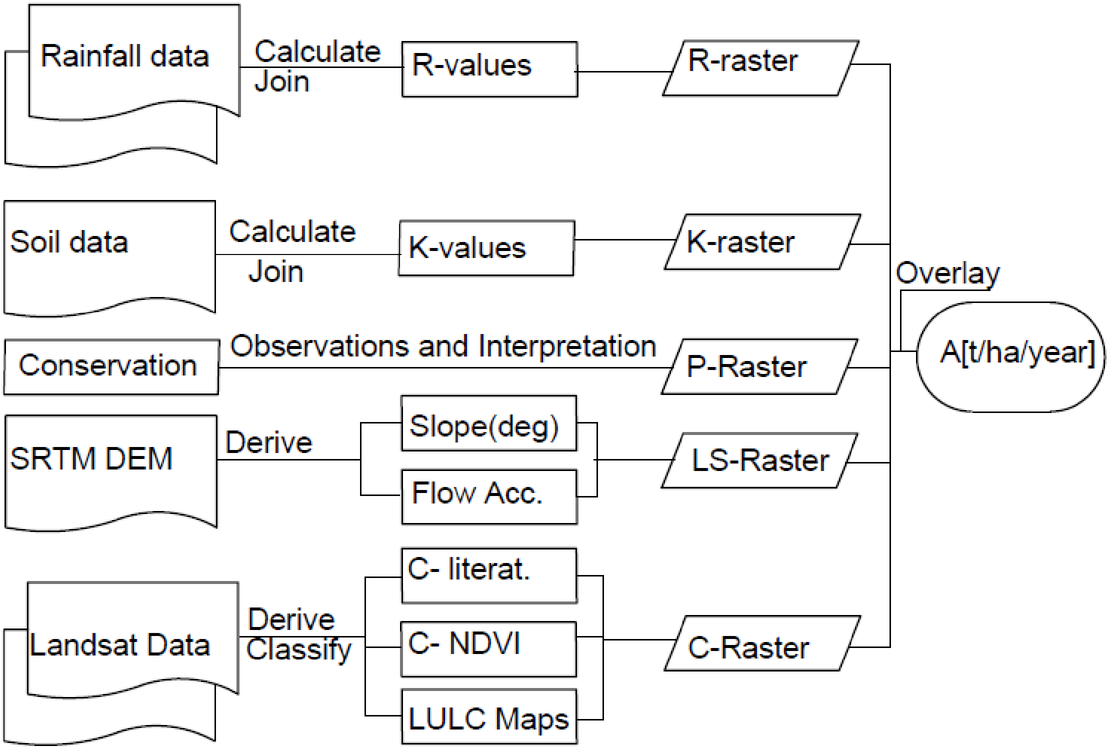

Figure A - 2 Average annual precipitation for the study watershed between 1990 to 2012 for 13 stations.

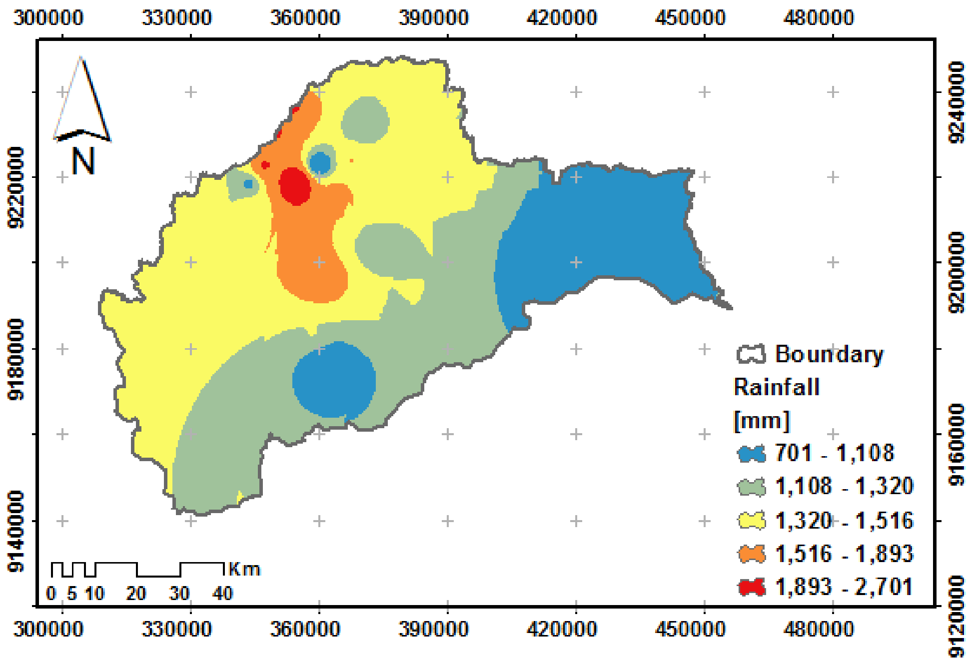

Figure A - 3 Distribution of K-factor values within the watershed

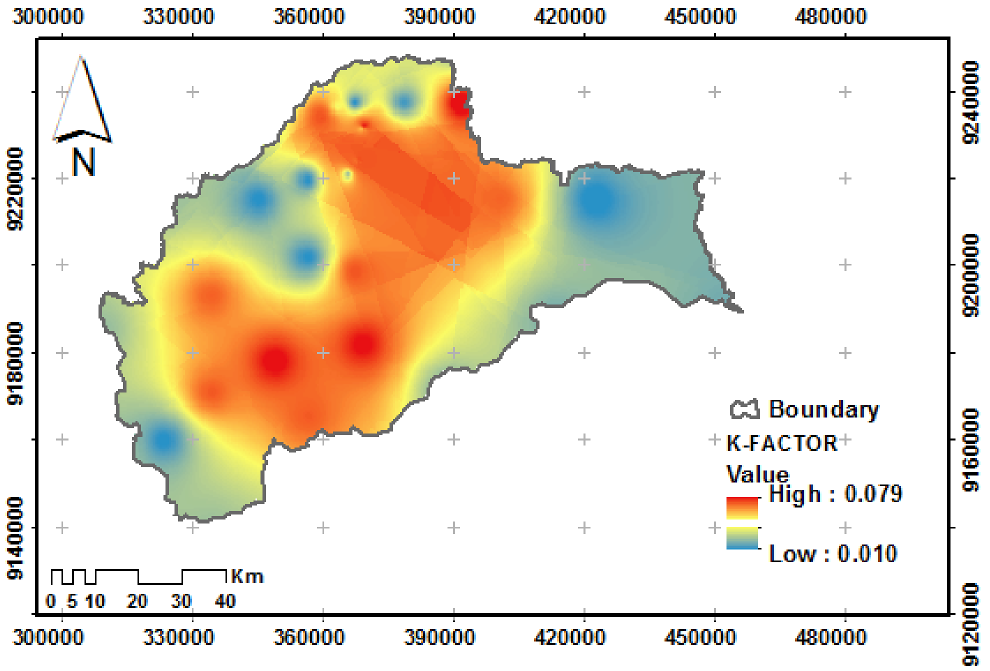

Figure A - 4 Major soils found in the Upper Ruvu watershed.

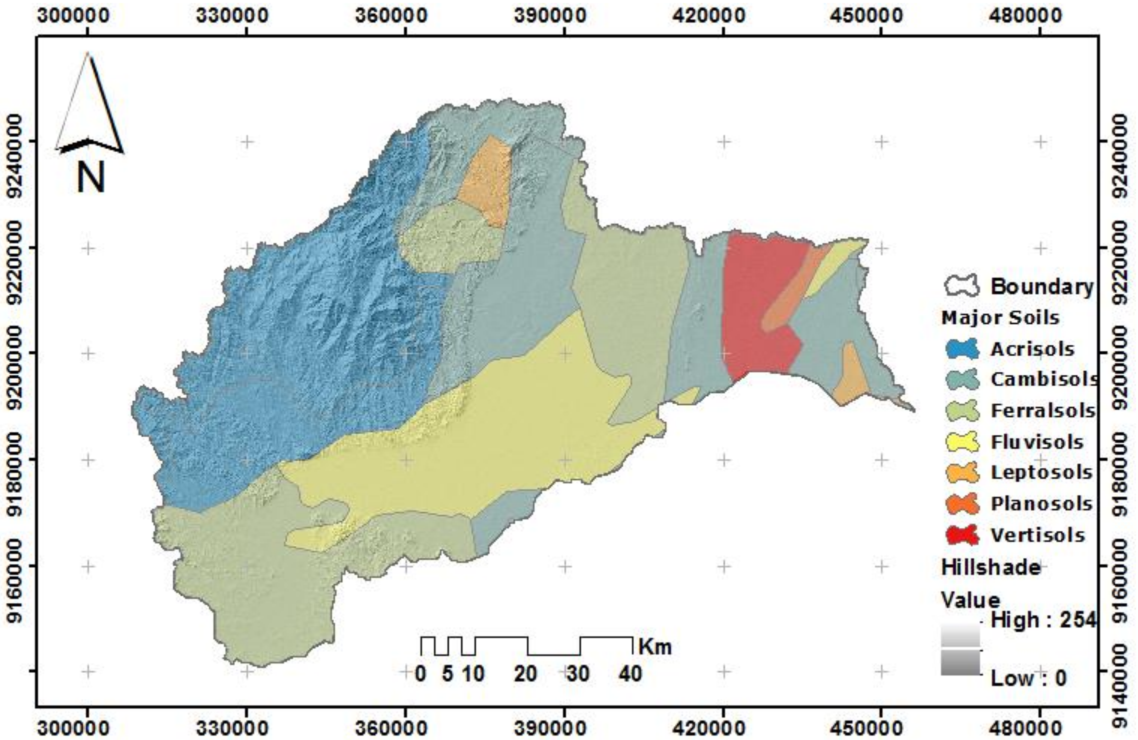

Table A - 1 Accuracy Assessment of LULC Maps for the Upper Ruvu Watershed (1991, 2000, 2015)

Land Cover	1991		2000		2015	
	PA	UA	PA	UA	PA	UA
Natural Forest	95	95	89	98	99	97
Shrubland	91	91	93	89	94	91
Cropland and Rural Settlement	91	86	92	92	91	87
Woodland	91	94	93	86	94	97
Grassland	97	98	89	88	92	95
Bareland	99	96	94	86	92	88
Water	93	81	96	88	95	81
Wetland	97	99	87	95	96	98
Clouds and shadows	100	99	98	98	89	91
Overall Accuracy	93		91		93	
Kappa Coefficient	91		89		92	

PA = Producer's Accuracy, UA = User's Accuracy

Table A - 2 Average C-factor values from literature

Land cover class	C-factor
Natural Forest	0.003
Shrubland	0.2
Cultivated land and settlement	0.56
Woodland	0.07
Grassland	0.15
Bare land	0.6
Water	0.001
Wetland	0.001
Clouds and Shadows	0.0

Source: Morgan (2009), Wischmeier and Smith (1978)

Table A - 3 Change Area of different land cover classess for the three time periods

Land Cover	1991-2000		2000-2015		1991-2015	
	Area change(Km^2)	%	Area change(Km^2)	%	Area Change(Km^2)	%
NF	-522	-40.5	-472	-61.5	-994	-77.1
SH	243	21.3	198	14.3	441	38.6
CR	519	49.5	649	41.4	1168	111.5
WD	-346	-15.9	-613	-33.6	-959	-44.2
GL	259	29.3	384	33.6	642	72.7
BL	-0.2	-0.1	108	61.3	108	61
WR	-22	-19.9	-53	-59.4	-75	-67.5
WE	-123	-18.4	-212	-39.1	-336	-50.3
CS	2	10.2	51	303.2	52	344.5

NF-Natural Forests, SH-Shrubland, CR-Cropland and rural settlement, WD- Woodland, GL-Grassland, BL-Bareland, WR-Water, WE-Wetland, CS-Clouds and shadows

Table A - 4 Monthly Rainfall data from stations used in the calculation or R-factor

Month	Matombo	Morningside	Tegetero	Mkuyuni	Hobwe	Mikula	Tawa	Bwakira	Bwakira Juu	Mzungu Mgeta	Bunduki	Mvuha	Kienzema	Singiza
Jan	147.88	135.61	177.78	181.01	85.04	53.07	148.51	105.3519	187.01	113.17	172.70	142.43	171.23	118.4882
Feb	132.64	136.11	206.14	149.64	67.13	58.57	91.94	112.22	198.98	133.88	152.79	125.75	159.85	127.9
Mar	209.98	279.64	378.55	242.01	129.87	87.54	210.23	169.66	278.86	167.23	267.56	198.53	213.44	287.37
Apr	266.89	534.38	491.80	321.06	187.04	151.11	294.55	248.3542	298.91	256.12	355.26	230.14	317.57	289.4286
May	137.42	348.23	281.40	147.05	85.21	61.15	172.55	99.15263	142.77	57.87	160.85	100.31	135.81	155.6231
Jun	57.89	97.26	114.36	44.59	11.91	20.55	73.27	34.67143	53.23	8.58	32.99	24.00	35.14	51.21111
Jul	50.61	71.89	83.77	37.52	5.93	12.58	69.83	21.9619	49.52	8.07	21.46	15.96	20.10	23.84118
Aug	43.51	74.24	105.06	32.23	5.21	11.11	94.18	10.24	37.63	6.34	47.36	25.37	8.11	26.72105
Sept	46.50	64.28	100.45	45.05	8.18	10.67	65.90	18.14444	57.03	21.55	77.22	34.88	23.47	26.29412
Oct	87.87	145.87	150.88	80.99	33.85	46.28	134.31	35.51111	120.48	45.60	144.60	55.36	40.91	64.94375
Nov	132.09	181.35	228.00	132.52	59.64	81.28	175.11	83.87	119.55	91.72	260.47	91.75	111.10	99.3
Dec	192.13	197.25	224.04	202.69	85.36	80.71	198.77	78.65263	223.29	127.27	249.82	115.76	174.03	116.3
Average	125.45	188.84	211.85	134.70	63.70	56.22	144.10	84.82	147.27	86.45	161.92	96.69	117.56	115.62

Table A - 5 Sample Soil Analysis Results from the Lab

SN	Field	Depth	LAB	Soil pH (1:2.5)	EC	P.S.D.			Text	OC-BlkW	Ext.P (mg/kg)		CEC (cmolKg-1)	Exch. Bases (cmolKg-1)			
	ref		No.	(in H_2O)	MS/cm	% Clay	% Silt	% Sand	Class	(%)	PBry-1	Ols	CEC	Ca^{2+}	Mg^{2+}	K^{2+}	Na^{2+}
1	MK/P3	0-15/20	**S/1818/2015**	6.61	0.070	22	10	68	SCL	1.52	0.99		18.00	29.10	4.68	0.11	0.09
2	MK/P3	15/20	**1819**	6.86	0.030	24	10	66	SCL	0.37	0.53		13.60	27.20	3.08	0.08	0.12
5	MK/P3	55-100	**1822**	5.89	0.02	52	12	36	C	0.43	1.59		12.20	9.07	1.68	0.46	0.09
6	MK/P3	100-130	**1823**	5.82	0.02	44	14	42	C	0.20	0.46		8.60	7.80	1.40	0.06	0.09
3	MK/P2	0-15/20	**1820**	6.3	0.080	52	10	38	C	2.01	3.24		19.80	4.37	1.07	0.74	0.07
4	MK/P2	15/20-55	**1821**	6.04	0.030	64	8	28	C	0.60	0.73		9.80	8.43	1.51	0.17	0.06
7	MK/P2 BCg	130-200+	**1824**	5.71	0.02	34	16	50	SCL	0.04	0.47		9.80	7.48	1.60	0.05	0.10
8	MK/P4	0-20/35	**1825**	6.27	0.040	70	8	22	C	1.50	1.65		10.60	0.82	0.38	0.29	0.08
9	MK/P4	35-60	**1826**	6.02	0.040	80	2	18	C	0.53	0.99		6.80	4.63	1.25	0.05	0.08
10	MK/P4	60-95	**1827**	6.03	0.030	80	4	16	C	0.27	0.93		6.20	1.46	1.36	0.04	0.08

11	MK/P 4	95-140	**1828**	6.1	0.030	82	4	14	C	0.25	0.93		5.00	2.09	1.15	0.04	0.08
12	MK/P 4	140-200+	**1829**	5.75	0.040	80	4	16	C	0.23	0.73		5.00	0.82	1.18	0.04	0.08
13	KN/P 1 AP	0-10/15	**1830**	6.18	0.060	42	6	52	SC	0.47	4.89		7.40	10.34	1.36	0.37	0.07
14	KN/P 1 BA	10/15-25/30	**1831**	6.07	0.080	50	6	44	C	0.72	0.93		6.80	3.99	1.19	0.41	0.07
15	KN/P 1	28/30-60	**1832**	5.92	0.020	52	6	42	C	0.53	0.46		5.60	1.14	0.45	0.42	0.08
16	KN/P 1 Bt2	60-120	**1833**	5.72	0.020	50	8	42	C	0.04	0.26		4.80	1.14	0.03	0.14	0.09
17	KN/P 1 BC	110-200+	**1834**	6.33	0.020	38	16	48	SC	0.16	0.28		5.20	0.82	0.02	0.29	0.09

Table A - 6 Locations from which Soil Samples were taken

SNo	Pno.	Lat	Long	Altitude	Soil	Texture
1	1	-6.91	37.76	532	Acrisols	SC
2	2	-6.95	37.81	407	Cambisols	C
3	3	-6.95	37.82	361	Leptosols	SCL
4	4	-7.05	37.78	302	Ferrasols	C
5	F1D1	-6.93	37.73	190	Ferrasols	SCL
6	F2Dw	-7.02	37.80	298	Ferrasols	SCL
7	G1P1	-7.01	37.81	258	Ferrasols	SCL
8	F6PLOT6	-7.01	37.81	352	Ferrasols	SCL
9	F4PLOT4	-7.01	37.81	286	Ferrasols	SCL
10	G2P1	-7.02	37.81	189	Ferrasols	SC
11	G6P6	-7.02	37.81	147	Ferrasols	SL
12	G3P3	-7.02	37.81	214	Ferrasols	SC
13	G5P5	-7.02	37.81	213	Ferrasols	SCL
14	G4P4	-7.02	37.81	218	Ferrasols	SCL
15	F5PLOT5	-7.02	37.80	257	Ferrasols	SCL
16	F3PLOT3	-7.02	37.80	284	Ferrasols	SCL
17	C2PLOT2	-6.93	37.73	758	Acrisols	C
18	C2PLOT3	-6.93	37.73	715	Acrisols	C
19	C1P..	-6.93	37.73	694	Acrisols	SCL
20	F2W1	-7.02	37.80	293	Ferrasols	SCL
21	Kolero	-7.25	37.8	357	Cambisols	SC
22	22	-7.44	37.63	162	Fluvisols	SCL
23	23	-7.40	37.81	146	Fluvisols	SC
24	24	-7.06	37.70	826	Acrisols	SCL
25	25	-7.22	37.70	1860	Acrisols	SCL
26	26	-7.60	37.40	348	Acrisols	SCL
27	27	-7.10	38.10	195	Ferrasols	SC
28	28	-6.90	38.02	266	Ferrasols	SCL
29	29	-6.90	37.90	540	Leptosols	SCL
30	30	-6.90	37.80	1002	Cambisols	SCL
31	31	-7.50	37.50	221	Ferrasols	SCL
32	32	-7.30	37.50	390	Acrisols	SCL
33	33	-7.55	37.70	289	Ferrasols	SCL
34	34	-7.10	38.30	116	Vertisols	C
35	35	-7.10	37.60	1963	Acrisols	SCL

Table A - 7 Rainfall Coefficient of Uniformity (CU) for simulated rainfall events

Land Use	Plot	Rain1(mm)	Rain2(mm)	Rain3(mm)	Rain4(mm)	Rain5(mm)	CU
Forest	1	60	61	70	51	80	0.87
Forest	2	60	66	77	84	75	0.90
Forest	3	65	61	54	44	60	0.95
Forest	4	63	66	73	71	65	0.95
Forest	5	63	63	85	71	73	0.91
Forest	6	61	72	95	83	72	0.87
Forest	7	71	63	77	90	61	0.88
Forest	8	79	76	98	99	73	0.87
Forest	9	71	71	53	87	64	0.88
Forest	10	78	66	72	90	83	0.91
Forest	11	77	65	79	65	75	0.92
Forest	12	79	71	71	61	73	0.94
Grassland	1	78	73	87	71	91	0.91
Grassland	2	70	79	79	55	54	0.85
Grassland	3	84	74	70	91	55	0.86
Grassland	4	81	73	63	110	59	0.81
Grassland	5	86	76	96	76	50	0.85
Grassland	6	80	80	82	76	53	0.89
Grassland	7	70	75	97	90	57	0.84
Grassland	8	78	70	42	89	55	0.78
Grassland	9	80	65	62	79	47	0.85
Grassland	10	77	70	70	70	41	0.85
Grassland	11	78	70	90	102	65	0.85
Grassland	12	80	60	41	100.5	52	0.72
Cropland	1	74	91	70	68	49	0.86
Cropland	2	80	61	67	47	58	0.86
Cropland	3	74	41	71	98	45	0.72
Cropland	4	76	99	50	39	78	0.86
Cropland	5	76	74	77	49	57	0.84
Cropland	6	74	75	79	93	42	0.83
Cropland	7	74	78	81	72	46	0.86
Cropland	8	74	73	89	89	58	0.87
Cropland	9	78	74	76	74	45	0.86
Cropland	10	76	73	80	85	60	0.91
Cropland	11	72	81	76	83	67	0.86
Cropland	12	56	82	67	78	72	0.86
				Average UC			**0.86**

Figure A - 5 Hydrologic Soil Groups of Upper Ruvu watershed.

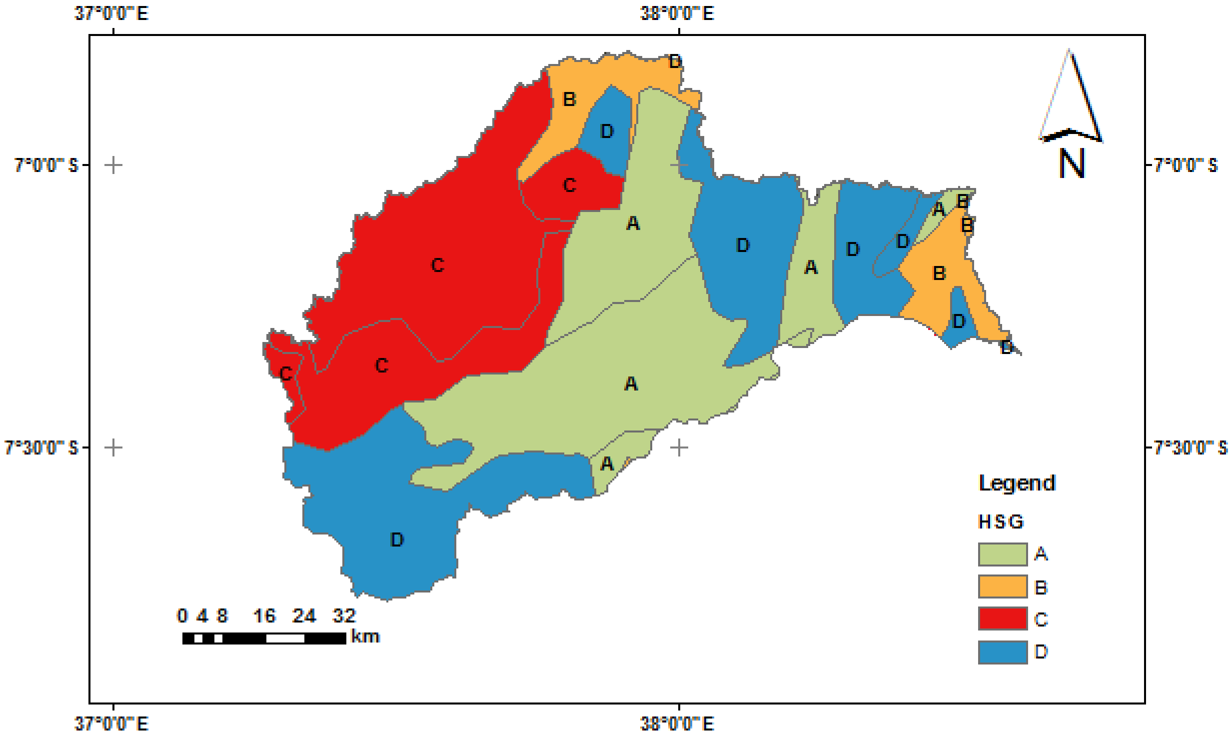

Figure A - 6 Evapotranspiration trends