UNIVERSITY of the WESTERN CAPE

Assessing land use-land cover changes and their effects on the hydrological responses within the Nyangores River Catchment, Kenya

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Department of Earth Sciences, Faculty of Natural Science, University of the Western Cape

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KEY WORDS

Sub-humid catchment

Landsat 8

Population increase

Land use intensification

Bulk density

Infiltration

Actual evapotranspiration

Surface Energy Balance System (SEBS)

Soil water content

ML3 ThetaProbe

Hydrus-1D

Plot scale

Runoff

Streamflow

Indicators of Hydrologic Alteration (IHA)

ABSTRACT

This thesis aimed at contributing knowledge on how the widespread changes in land use/cover resulting from increasing human population and their associated activities, are influencing hydrological responses in a sub-humid catchment. The study therefore hypothesised that reduced forest cover over time in favour of agricultural activities is altering hydrological processes of the catchment which is affecting the flow characteristics in a sub-humid catchment. The sub-humid catchment selected to investigate these issues is the Nyangores River Catchment in Kenya. The study had the following objectives; (i) to establish the nature and extent of land use/cover changes and how population dynamics have contributed to these changes, (ii) to establish the nature and causes of land use intensification, (iii) to determine the responses of evapotranspiration rates, soil water and runoff generation to land use/cover changes in a sub-humid catchment, and iv) to assess whether land use/cover changes have caused significant changes to long-term river flow characteristics in a sub-humid catchment. Data sets from various sources that were used; a) Landsat satellite images obtained from the websites and used for land use/cover change detection and for estimation of evapotranspiration; b) secondary data including meteorological data from the Kenya Meteorological Department, (KMD), population census data from the Kenya National Bureau of Statistics (KNBS) and river discharge data from Water Resources Management Authority (WRMA), and; c) primary social and hydrological data. The various methods to analyse data are described in details in the chapters where they were applied. Some of the unique analysis methods in this thesis include the use of Hydrus-1D in simulating soil water at various depths to detect variability in soil water in different land use/cover types in a catchment with scarce data. The use of Surface Energy Balance System (SEBS) enabled estimation of evapotranspiration rates for the different land use-land cover types. This study established a significant reduction (by 55%) of forest cover over a period of 36 years, much of which was converted to subsistent croplands and wooded grasslands. The population and households increased rapidly over this period which led to increased use of forest resources. Land use intensification was characterised by high land use intensity with 95.7% of farms put under semi and permanent cultivation through reduced fallow periods. Forest had significantly higher mean evapotranspiration rate (ET_a) rate (5.98 mm/day) compared to the other land cover types with the built up areas having the lowest. However total water lost in the catchment through ET has reduced over time as the forest cover diminished. Land use/cover changes have significantly altered soil properties in the catchment in such a way that soil bulk density (BD) had increased and soil organic carbon (SOC) reduced in the cropland compared to the undisturbed (wooded grassland and forest) lands. The infiltration rate of water in the cropland reduced by three times compared to areas under forest. The altered soil properties have consequently changed soil water and surface runoff characteristics within the catchment. The overall impact of land use/cover changes and alterations of hydrological systems have impacted on Nyangores River flows over the years; there was significant increase of low flows and base flows with no significant changes of peak flows. It was concluded that reduction of evapotranspiration due to reduced forest cover have led to the increased low flows. In this study therefore, the impacts of the replacement of forest with farming on catchment hydrology were established. This was made possible particularly through the application of various data acquisition methods and modelling approaches. This study contributes to land and water resource management. It gives a good insight on land cover changes stemming from human activities in examining the driving factors of the changes which have implications on hydrological process in the catchment with focus on a farm level.

DECLARATION

I declare that this Thesis "**Assessing land use-land cover changes and their effects on the hydrological responses within the Nyangores River Catchment, Kenya"** is my own work and has not been presented before for any degree or examination in any other university and that all the information sources I have used or quoted have been indicated and acknowledged by means of complete references.

Margaret Njoki Ndungo

Signature October, 2021

DEDICATION

This work is dedicated to the entire Ndungo family starting with the head of the family my husband Moses Ndungo Wanjara, my children, Samuel Wanjara, Priscilla Nyambura and nephew Samuel Wanjara Wachera. A lot of dedication also to my brother Joseph Njuguna Mwangi who was my driver in the field.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
BD	Bulk Density
DEM	Digital Elevation Model
DJF	December–January-February
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
ET_a	Actual Evapotranspiration
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization
FVC	Fractional Vegetation Cover
GIS	Geographic Information Systems
GLCF	Global Land Cover Facility
GOK	Government of Kenya
IHA	Indicators of Hydrologic Alteration
ILWIS	Integrated Land and Water Information System
ISRIC	International Soil Reference and Information Centre
JJA	June-July-August
KMD	Kenya Meteorological Department
LAI	Leaf Area Index
LPDAAC	Land Processes Distributed Active Archive Center
m.a.s.l	Metres above sea level
MAM	March-April-May
METRIC	Mapping Evapotranspiration at High Resolution with Internal Calibration
MODIS	MODerate Resolution Imaging Spectroradiometer
MSS	Multi Spectral Scanner
NDVI	Normalized Difference Vegetation Index
OLI-TIRS	Operational Land Imager and Thermal Infrared Sensor
OND	October-November-December
RC	Runoff Coefficient
RGS	Regular Gauging Station
SEBAL	Surface Energy Balance Algorithm for Land
SEBS	Surface Energy Balance System

SOC	Soil Organic Carbon
SON	September-October-November
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapper
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WARMA	Water Resources Management Authority of Kenya

CHAPTER 1: INTRODUCTION

1.1 Introduction

Activities of a rapidly increasing human population have resulted in significant land use/cover changes. The increased land use/cover changes and human population have resulted in deforestation and changes in farming methods which have affected the water balance. According to most studies, (Mutiga et. al., 2011; Näschen et.al., 2019; Samal & Gedam, 2021), deforestation and farming methods have the potential to alter soil properties hence affecting the hydrological processes. Regional and local studies have indicated changes in land cover and farming methods in the world (Lambin et. al., 2003; Palamuleni et. al., 2011; Sivapalan et. al., 2012; Assefa et. al., 2020; Lai & Kumar, 2020). However, most of these studies are undertaken at coarse spatial resolution and the results may not be applicable at local (catchment) scale. The effects of the local farming practices and changes in soil properties at farm level that may lead to hydrological changes are usually not taken into consideration in most of these studies.

Studies that have investigated possible changes of spatial and temporal characteristics of land use/cover and how they influence hydrology over the East African region are few. For instance, Kashaigili and Majaliwa (2013) examined land use/cover modifications in Malagarasi River Catchment in Tanzania and observed a significant deforestation in favour of croplands which resulted in decreased dry season flows. Chilagane et. al. (2021) observed that land use/cover changes in the little Ruaha River Catchment in Tanzania caused annual decrease in base flow and an increase in annual surface runoff. Mati et. al. (2008) investigated land use/cover changes in Mara River Basin (Kenya) and observed that over the period between 1973 and 2000, there was increased flood peak flows and reduced low flows in the Mara River. Mwangi et. al. (2016) observed increased discharge in the Nyangores River between 1965 and 2007 which was attributed to increased base flow after deforestation in the Nyangores River Catchment. The aforementioned studies do not have a consensus as to the effects of deforestation on hydrological processes particularly in the East African catchments. Some studies argue that deforested catchments are characterized by increased dry river flows due to decrease of evapotranspiration (Bruijnzeel et. al., 2004). Bruijnzeel and Bremmer (1989), and Bruijnzeel (2004) also asserts that dry season flows may decrease if the compaction in croplands and grazed areas impedes infiltration so much as to exceed the benefits of the reduced evapotranspiration (that of increased dry season flows). This begs the question as to whether the resulting land use/cover after deforestation have increased evapotranspiration to the extent that river flows have reduced in these catchments. The aforesaid studies in East Africa have used rainfall and runoff processes to indicate the effects of land use/cover changes on hydrology which may not give conclusive evidence for change. Lettenmaier et. al. (2009) argues that sound assessment of human interference in the water cycle should be carried out by observing trends in all key hydrological variables such as streamflow, evaporation, soil water, precipitation, groundwater, water storage in lakes and wetlands. Moreover, rainfall and runoff are not the only factors that indicate alterations to hydrological processes in a catchment. Most studies on rainfall and runoff have been done at a catchment scale and the results cannot be used to manage water at the farm level due to the uncertainties encountered while downscaling the findings (Cerdan et. al., 2004; Samal & Gedam, 2021). Previous studies in East Africa have not yet investigated possible alterations of soil properties due to increased agricultural activities and their impacts on soil water and runoff generation. This thesis, sought to contribute to improved understanding of how changes of land use/cover and subsistence agricultural practices may influence soil properties which could eventually alter soil water movement, runoff and evapotranspiration which are important for land and water resource management. A concise discussion of the gaps in research that exist in this respect is given below.

1.1.1 Land use/cover and population changes

Studies on changes of land use/cover have been done in several catchments all over the world. Most studies investigate the factors contributing to the changes in land use/cover particularly human activities as the world population increases. The factors that have been attributed to greatly contribute to land use/cover changes through deforestation in different parts of world include migration of people who settle as refugees, increased population densities, expansion of land for agricultural and settlements, and other socioeconomic factors (Zak et. al. 2008; Kashaigili and Majaliwa 2013; Ayuyo and Sweta 2014; Rotich & Ojwang, 2021). Leslie et. al. (2018) reported that deforestation could also result from poor enforcement of laws. Although these studies indicate that population increase causes alterations in land use/cover particularly through, deforestation, they do not show how population dynamics influence land use/cover changes at a local (catchment) scale even when forests are protected by governments. This is important because cultural practices regarding resource consumption such as hunting, subsistence agriculture are unique depending on specific areas.

1.1.2 Land use intensification

In recent times governments in many parts of the world have introduced laws in an effort to curb further destruction of forests. This has resulted in diminishing of land for agriculture as population increases which has led to intensified use of the available land. Land use intensification practices include the increased frequency of cultivation and use of technology such as mechanization (Carswell, 1997; Nambiro, 2007). Land use intensification form of farming is nowadays very common all over the world mainly due to population increase as was theorised by Boserup in (1965). Numerous studies have been carried out on the influence of human population on changes in land use. For instance, Codjoe et. al. (2011) reported that in Ghana land use intensification is done through the use of reduced fallows and increased mechanization. Nambiro (2007) studied land use intensification in Kakamega in Kenya and reported that farmers were practising permanent cultivation through expanding the cropping by reducing the fallow periods. The farmers are also increasing cropping intensity through inter-cropping and multi-cropping. Saka (2011) showed that land use intensification in south-western Nigeria was associated with frequent cultivation and intensifying cropping activities. All these studies suggest intensification is being pursued more vigorously at the global level for increased food production (DeClerck et. al., 2016). However, since land use policies that influence land utilization are unique to different countries (Lele &Stone, 1989), and land use intensification strategies depend on the economic ability of the farmer among other factors (Nambiro, 2007), these findings are not applicable to all situations. Hence, the need to explore the kind of land use intensification methods being employed by farmers in developing countries where available per capita land for agriculture is diminishing as population increases. These changes have the potential to impact negatively on the hydrologic processes of a catchment. The Nyangores River Catchment where this study is carried out, is in the sub-humid equatorial region and the main agricultural practice is subsistence farming. Information on land use is vital for policy formulation in water resources management because land plays a key role in the water balance.

1.1.3 Effects of land use/cover on hydrological responses

Evapotranspiration

Evapotranspiration (ET) is a principal factor in the hydrological cycle that has been widely studied. Understanding ET is important in understanding the human influence on water balance (Nsiah et. at., 2021). ET is a function of both meteorological and land use/cover. The studies that examine the response of a catchment to evapotranspiration after land cover changes reveal various trends depending on climate and the methodology used. For instance, Odongo (2016) reported that in Naivasha evergreen forest and closed shrub lands had the highest annual ET while grasslands and savannas had the lowest annual ET. Mwangi et. al. (2016) reported that evapotranspiration over Nyangores River Catchment was decreasing and attributed this decrease to changes in catchment properties rather than climatic factors. Another study by Gong et. al. (2017) used eddy covariance to estimate ET in a degraded and rehabilitated lands and reported an increase in ET that was attributed to the effects of the changes in vegetation type, topography and soil surface conditions in a semi-arid shrub land in the Mu Us sand land (China). These studies indicate that land use/cover changes influence changes in ET. However, due to differences in the climatic and the prevailing socio-economic factors, these changes are catchment specific and may not be generalized. The methods used to estimate ET are also not universal and may cause differences even in similar catchments. For instance, Mwangi et. al. (2016) studied trends in ET over the Nyangores River Catchment using a water balance and concluded that evapotranspiration is decreasing. However, since this study was done at a catchment scale, the results may not be used to manage water at farm level where human activities take place. Again, Lambin et. al. (2006) highlights that the impacts of land use change on surface radiation budgets and hydrology is complex and does not allow generalization due to variability in seasons and soil conditions at the scales the studies are done. Therefore, for water resource management at catchment level, there is need for characterization of ET in the different land cover types. This type of study is important in a sub-humid equatorial catchment such as the Nyangores River. The study intends to increase the understanding of the influence of ET on water availability in a catchment.

Effects of land use/cover on soil water content

Soil water plays a key role in plant growth and restoration of vegetation in many catchments. Soil water is also significant in the water balance. The spatial variability of soil water is mainly controlled by topography, soils, vegetation and land use (Fu et. al., 2003; Gao et. al., 2014; Mekki et. al., 2018; Guo et. al., 2020; Wang et. al., 2020). Land use /cover change can significantly alter the soil structure and the vegetation resulting in alteration of soil water content. These alterations have implications on water availability in a catchment. Studies have reported alterations of soil water content in catchments following land use/cover changes in some parts of the world. Gao et. al. (2014) reported significant variation of profile soil water that was caused by changes in land use in the Chinese Loess Plateau between 2009 and 2010. Other studies indicate that cultivation and grazing reduced the plant cover at soil surface resulting reduced water content (Abdelkadir and

Yimer, 2011; Lai et. al., 2020). All these studies indicate that soil water content is dependent on the land use/cover types. Most of these studies have been conducted in the semi-arid regions that have water scarcity. However sub-humid regions that have undergone significant land use/cover changes through deforestation and other land transformations have not been adequately studied. This study endeavoured to investigate the spatial and temporal variations of soil water in Nyangores River catchment. The lack of enough knowledge on the soil water dynamics poses challenges in the understanding of hydrological and ecological processes in the catchment and therefore hindering the efforts of water resource management.

Effects of land use/cover on runoff generation

Runoff generation in a catchment mainly depends on the type of land use/cover and the rainfall characteristics. Under the same climatic condition (rainfall regime), the type of land cover is critical in runoff generation (Loaiza Usuga et. al., 2009; Chilagane et. al., 2021). For instance, Karamage et. al. (2017) observed an increase in runoff depth after a large-scale deforestation and reduction of grassland over a long period of time (over a decade) in Rwanda. Recha et. al. (2012) also reported an increase in runoff with increased cultivation in a 50 years old agricultural catchment in Western Kenya. Berihun et. al. (2019) observed increased runoff in Kasiry catchment in Ethiopia as a result of conversion of natural vegetation to cultivated lands. These studies indicate that runoff generation is significantly influenced by alterations of land use/cover in catchments. However, besides the effects of land use/cover changes, rainfall characteristics also influence runoff generation particularly in terms of intensity and duration. Furthermore, due to the nonlinearity nature of rainfall-runoff relationship brought about by the soil water, Rodríguez-Blanco et. al. (2012) recommends the incorporation of soil water conditions while determining the response of a catchment to runoff generation. Most studies in rainfall-runoff relationships model the catchment as hydrologic response units without considering how different land use/cover types respond to rainfall. In this study experimental plots were used to investigate the effects of land cover change on runoff generation.

1.1.4 Streamflow characteristics

Land use/cover changes in a catchment influences the most important factors in a water balance; *i.e*. runoff, soil water and ET. The outcome of a water balance in a catchment is manifested through streamflow characteristics. Some studies have examined the effects of land use/cover changes on streamflow at catchment scale (Yang et. al., 2008; Worku et. al., 2014; Fentaw et. al., 2017).

However, such studies fail to inform water managers on the water consumption in different land use/cover types where human activities mainly take place. On the other hand, studies focus on investigating how land use/cover changes affect hydrological processes at micro-scale (plot scale) (Girmay et. al., 2009; Defersha & Melesse, 2012; Taye et. al., 2013). However, the hydrological processes taking place at micro-scale may not necessarily be realized at the catchment scale hence posing challenges to water management (Bonell et. al. 2006; Sidle, 2006). Therefore, in order to examine whether the hydrological processes at plot scale (in different land use/cover types) are being experienced in the entire Nyangores River Catchment, the long-term streamflow characteristics were investigated. The results from the study would provide valuable information for the recommendations of water resource management in sub-humid catchments.

1.2 Research questions and objectives

The aim of this study was to increase knowledge about how land use/cover changes arising from increasing human population alter evapotranspiration rates, soil water, runoff generation and long-term river flow characteristics in a sub-humid catchment. To achieve this aim, this study attempted to answer the following questions:

1. What is the nature and extent of land use/cover change and how have these changes been influenced by population dynamics in a sub-humid catchment?
2. How have the population dynamics influenced land use intensification?
3. What have been the responses of evapotranspiration rates, soil water and runoff generation to land use/cover changes in a sub-humid catchment?
4. Are there any significant changes of long-term river flow characteristics that have occurred as a result of land use/cover changes in sub-humid catchments?

Objectives

To answer the above research questions, the following specific objectives were undertaken:

1. To establish the nature and extent of land use/cover changes and how population dynamics have contributed to these changes.
2. To establish the nature and causes of land use intensification.
3. To determine the responses of evapotranspiration rates, soil water and runoff generation to land use/cover changes in a sub-humid catchment.
4. To assess whether land use/cover changes have caused significant changes to long-term river flow characteristics in a sub-humid catchment.

1.3 Significance of the study

Numerous activities including reduction of forest land as a result of high population and subsequent increased cultivation are likely to impact on the hydrology of a catchment. With water being a key factor for developments, catchments face the risk of losing livelihoods and revenue that may be averted by water conservation measures that are possible through understanding of the current hydrological systems. Ondieki (2013) highlights that degradation of watersheds including declining water resources result to unsustainable environmental and socio-economic development requiring interventions from all stakeholders.

Many studies in the Nyangores River Catchment points to declining river discharges particularly the dry season flows (Mati et. al., 2008; Mango et. al., 2011; Mwangi et. al., 2016). For instance, Omonge et. al. (2020), highlight that Nyangores River Catchment experiences high water demands which exceeds water supply in dry seasons. Although studies in this catchment have been done on land use/cover changes and hydrology, it is important to understand the influence of the nature and effects of land use/cover changes on hydrological responses. This will improve the understanding of water management in sub-humid environments. Other studies in this catchment have employed rainfall-runoff models to investigate the hydrological response of the catchment after human activities (Mati et. al., 2008; Mango et. al., 2011). However, most rainfall-runoff modelling at the catchment scales only relate rainfall to runoff. However, considerations of soil water and evaporation rates in hydrological processes are important. The effects of land use/cover changes on soil properties and their influence on soil water (and hence the water balance) of many catchments has been reported globally (Molina et. al., 2007; Kavian et. al., 2014). Although such studies have shown that increased human activities in river catchments alters hydrological systems, no study has investigated the response of Nyangores River Catchment to the changes in soil properties/water content as land use intensifies. Furthermore, the influence of soil water content on runoff generation in this catchment need to be well understood. Hence, results from this study can be used to improve water resource management and build onto the spatial datasets for water management in the catchment (Olang et. al. 2019). Even as more evidence is gathered about the influence of land use/cover changes on evapotranspiration (ET) in the world (Gashaw et. al., 2017; Woldesenbet et. al., 2018; Berihun et. al., 2019), there is still limited information on the changes in ET over the sub-humid equatorial catchments such as the Nyangores River Catchment at the spatial scales needed to manage the dwindling water resources (Mwangi et. al., 2016; Odongo, 2016). Rigorous analysis and accurately estimating ET particularly using remote sensing technology could provide information on water variations at smaller spatial scales and at regular intervals that can enable water management even at farm level. ET rates over Nyangores River Catchment has not been studied at spatial scales that can provide knowledge on how the catchment is responding to land use/cover changes, although it has a significant effect on the catchment's water balance.

The hydrological changes in river catchments manifests in streamflow characteristics. The use of single flow indices applied in some studies (Mati et. al., 2008; Kashaigili & Majaliwa, 2013) may not allow the investigation of multiple impacts of hydrological changes. A multivariable approach is recommended in river flow studies (Shiau & Wu, 2004; Yang et. al., 2008; Worku et. al., 2014; Fentaw et. al., 2017). Lack of proper understanding of the multiple streamflow alterations may hinder improvement of water resource management in this catchment as population and agricultural activities continues to rise. Studies that have investigated how the Nyangores River has responded to the long-term changes in water balance components are scarce. Particularly changes in soil properties and soil water variability that influence river recharge have not been adequately investigated.

1.4 Outline of the thesis

The Thesis is organized in eight chapters whereby Chapter 1 gives an introduction to the study and Chapter 2 describes the study area. Chapters 3 to 7 addresses the research objectives as outlined in section 1.2. Chapter (3-7) are written as self-contained chapters with the relevant literature review and description of methods. This has been done because a) different research approaches and methods have been used to address the various research objectives, and the methods relevant for each objective are presented in the respective chapter, b) the author intends to modify each of the chapters into a peer-reviewed publication. Chapter 8 provides conclusions and recommendations of this study. The rationale of the choice of this structure of the thesis therefore leads unintentionally to repetition of some aspects such as description of study area and some key background issues. The following is a summary of the chapters;

Chapter 1 is an introduction to the general context of the research work provided in the thesis. This chapter provides the background information on the influence of population increase on land use/cover changes at global, regional and local scales; how human activities particularly farming practices are taking place, how land cover changes and farming practices have affected the response of hydrological processes such as soil water dynamics, ET, runoff and the streamflow characteristics. This chapter highlights the gaps in science relating land use/cover changes on hydrological processes, the main aim, research questions, specific objectives, and the justification of both the study and the study area.

Chapter 2 describes the geographical location of Nyangores River Catchment (study area), including climate, hydrology, economic activities, geology, soils, and the general vegetation.

Chapter 3 addresses the issues of land use/cover changes over time and how population dynamics have contributed to these changes in the Nyangores River Catchment. This chapter begins with a literature review of the relationship between population and land use/cover changes. Land use/cover change detection, satellite image analysis, accuracy assessment and further change detection re-analysis using post classification. This chapter also provides trends in population dynamics such as total population, households, population density, and consumption of forest resources in the catchment. This chapter provides results and discussion of the nature of land cover changes and the human population influence on these changes.

Chapter 4 addresses the nature and existence of land use intensification in the Nyangores River Catchment. This chapter provides a literature review on farming practices mainly the land use intensity, and tilling methods including how socio-economic factors are affecting land use intensification. The chapter outlines the method of data collection such as sampling frame and design of the questionnaire survey. This chapter provides results and discussion of the nature of land use intensification and its driving factors.

Chapter 5 investigates the influence of land use/cover change and land use intensification on the response of ET in the catchment using remote sensing by applying Landsat 8 satellite images and the energy balance algorithm. The Chapter outlines literature review on advances of remote sensing in determining ET using energy balance methods particularly the use of Surface Energy Balance System (SEBS). The chapter provides results and discussion of the catchment hydrological response to ET by different land cover types.

Chapter 6 examines the effect of land use/cover on soil properties and the influence of soil properties on the partitioning of rainfall into soil water and runoff. The chapter outlines the various data collection methods such as soil sampling for laboratory analysis, on site rainfall collection, experimental plots for runoff collection, soil water monitoring using ML3 ThetaProbe, and modelling of soil water content using Hydrus -1D model. The chapter provides results and discussion on soil water content in different land use/cover types and at five soil depths and also how different rainfall characteristics influence runoff generation.

Chapter 7 examines the streamflow characteristics of Nyangores River. The chapter outlines the use of Indicators of Hydrologic Alteration (IHA) software in computing the flow indices to be used in analysing streamflow changes over a period of 51 years. Particularly, this chapter explores if there were long-term changes in multiple flow indices and if these changes were attributable to the hydrological variations as a result of the land use/cover change observed in the catchment. long-term changes in rainfall and temperature (climate elements) were also investigated since they are factors that can cause change in streamflow. The chapter provides results and discussion on the streamflow characteristics and their possible association with the land use/cover change.

Chapter 8 provides the conclusion of the thesis by highlighting the main findings, significance and the implications of these findings to water resource management. The chapter also provides recommendations for further research work.

CHAPTER 2: STUDY AREA

2.1 Location of study area

The study was carried out in Nyangores River Catchment located (latitude: $0^o48.327'S$ to $0^o22.654'S$ and longitude: $35^o20.144'E$ to $35^o47.152'E$). The catchment is situated in a sub-humid climate in the south western region of Kenya. The catchment is the headwaters of the Mara River Basin in the Lake Victoria drainage basin. The catchment covers an area of approximately 737 km^2. The elevation varies from 1900 meters above sea level (m.a.s.l) in Bomet Town to 3000 m.a.s.l over the Mau Forest (Figure 2.1). The catchment area encompasses four districts; Nakuru District, Bomet District, Narok District and Buret District. Buret District is mainly forested while a large proportion of Narok District is also under forest (KNBS, 2009).

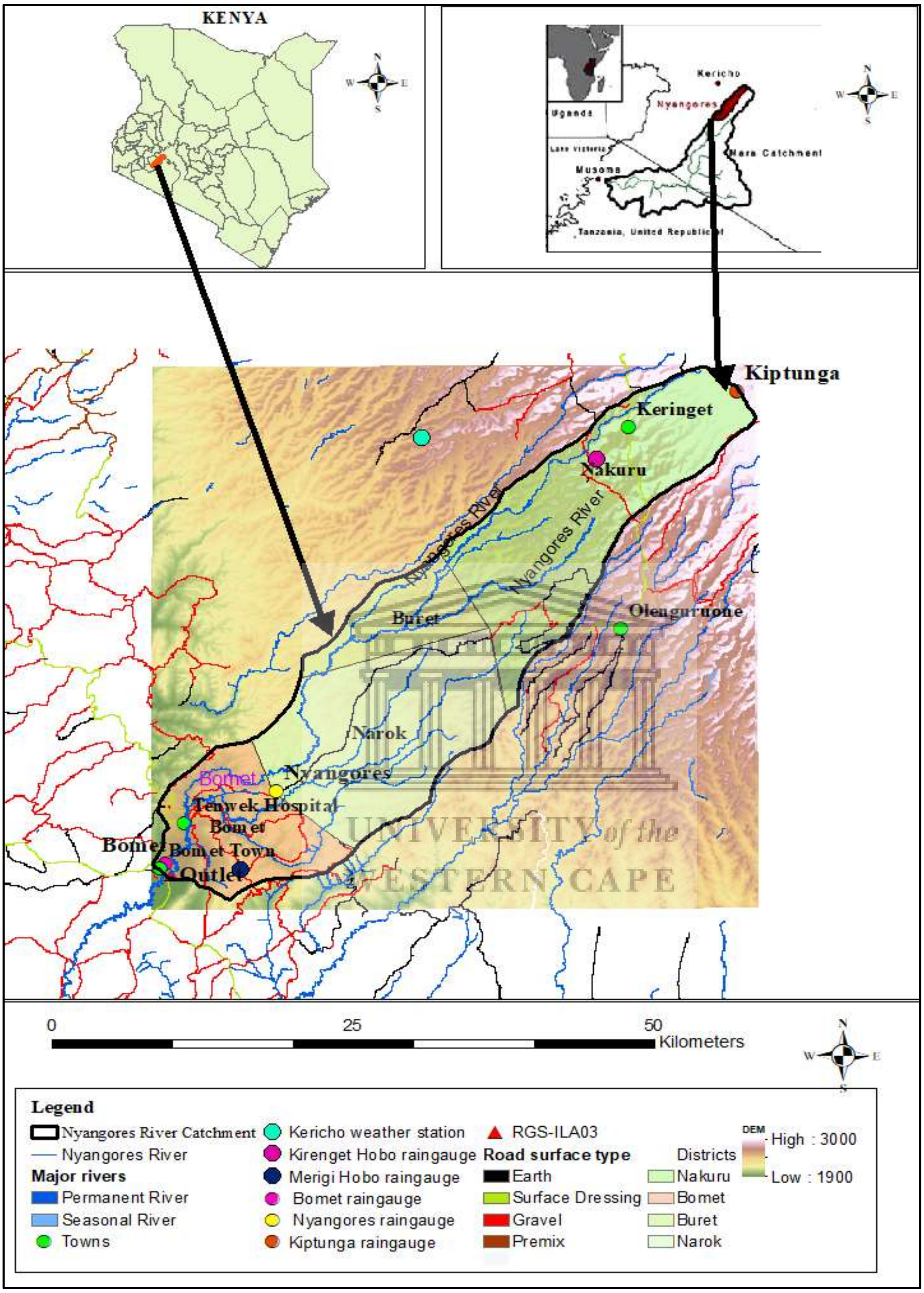

Figure 2.1: Nyangores River Catchment and the four districts considered in this study (Bomet, Narok, Buret and Nakuru). The inset maps show the location of the catchment in relation to Kenya and Mara River Basin. (Source: ArcGIS 10.2.2 (for desktop © 1999-2014 ESRI Inc.))

2.2 Climate

The climate of Nyangores River Catchment according to agro-climatic zones (based on moisture availability and temperatures zones) is sub-humid (International Livestock Research Institute (UNEP/GRID, 2017). The rainfall is controlled by the convergence of the northeastelies and southeastelies (trade) winds into the Inter-Tropical Convergence Zone (ITCZ) which is responsible for the seasonal variations of rainfall in the east African equatorial region. The catchment receives rainfall throughout the year with much of it occurring during the March to May (MAM) locally referred to as *long rains* and October to December (OND) referred to as *short rains* (Gachahi, 2016). However, a third smaller peak of rainfall occur in June-August season which is said to be caused by the influx of moist westerly airstream from the Atlantic Ocean and tropical Congo rainforest air mass (Mutai et. al., 1998 as cited in Ogwang et. al., 2015). The mean annual rainfall in the catchment is 1400 mm/year (Figure 2.2a). The area experiences mean annual minimum temperatures of 11.3°C and maximum of 24.3°C (Figure 2.2b). The long term average potential evapotranspiration is 1490 mm/year (Juston et. al., 2014).

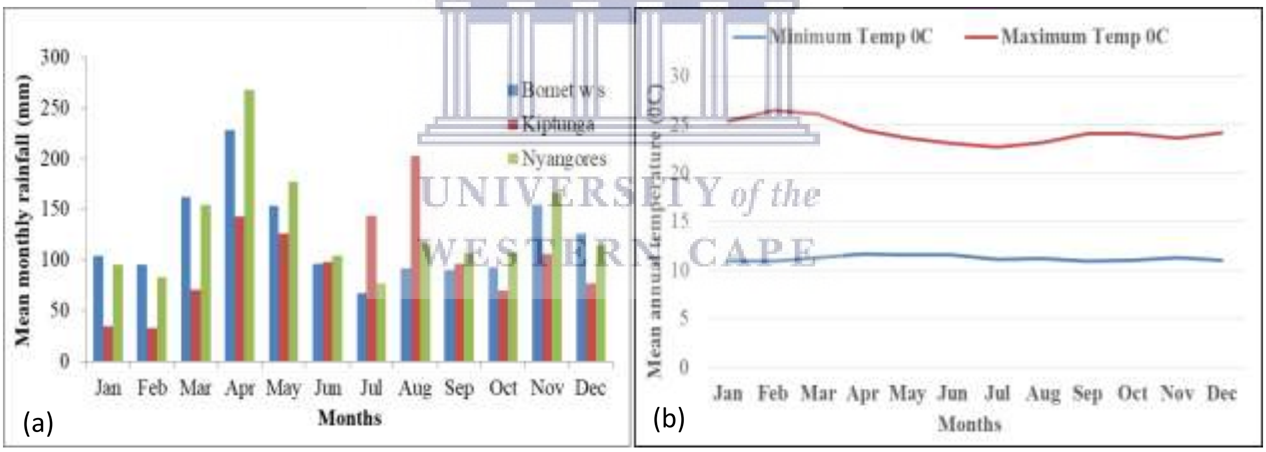

Figure 2.2: (a) Mean monthly rainfall distribution from 1980-2009 at Bomet, Nyangores and Kiptunga rainfall stations (b) Mean annual maximum and minimum temperatures for the catchment.

2.3 Hydrology

The Nyangores River originates from the Mau Forest and exits the catchment at Bomet Town after draining an area of 737 km^2. The river has several tributaries. The river discharge is measured at a river gauging station ILA03 (see Figure 2.1). The gauging station has three staff gauges and a rectangular weir that impounds the river for the purpose of water abstraction for water supply of Bomet Town (MRWUA 2011). The mean monthly streamflow from 1965-2016 shows that the catchment gets a mean monthly discharge of as high as 15 m^3/s in May and 12 m^3/s in September before it drops to below 4 m^3/s, during the dry season (January, February and March) (Figure 2.3).

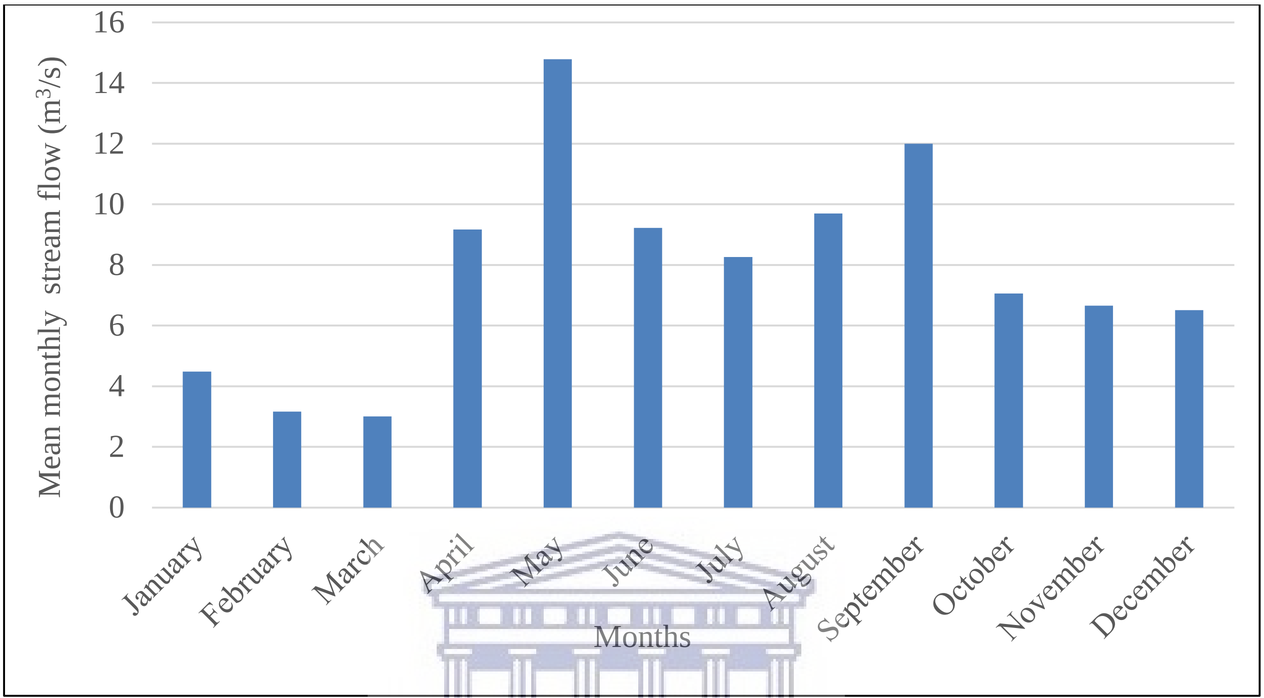

Figure 2.3: Mean monthly streamflow for Nyangores River 1965-2016 at Bomet ILA03.

2.4 Economic activities

The economic activities in the catchment include crop farming with tea being grown as a cash crop mainly in the upper and middle parts of the catchment. Much of the tea growing is done by many farmers at small scale although large scale tea farming is done at Kiptagich. Other crops grown across the catchment are maize, potatoes, beans, cabbages and onions (Kilonzo, 2014). Livestock rearing at subsistence level is common being done by 62% of the households (Aboud et. al., 2002). Forest is found in the middle part of the catchment at an altitude of about 3000 m.a.s.l (see Figure 2.6). The forest has a variety of tree species and experiences varying levels of degradation due to activities such as charcoal burning, llegal logging for both domestic and commercial purposes including honey harvesting (Kinyanjui et. al., 2013). In the lower part of the catchment sand harvesting mainly for local use is a common activity.

2.5 Geology

The Nyangores River Catchment comprises mainly of lava and pyroclastic. Episodes of Tertiary volcanic deposition produced the current Mau volcanic suite. The geological formation of the study area is characterized by the Mau Phonolites and Mau Tuffs. The Mau Phonolites (Miocene) consists of sheared sedimentary deposits, lavas, granites, pyroclastics and others, while the Mau Tuffs (Pliocene) has a thin layer of brown red soils underlain by compacted aggromerates of volcanic ash, pebbles and boulder sized pyroclastics (Figure 2.4) (Mati et. al., 2008; ESIA Report, 2017).

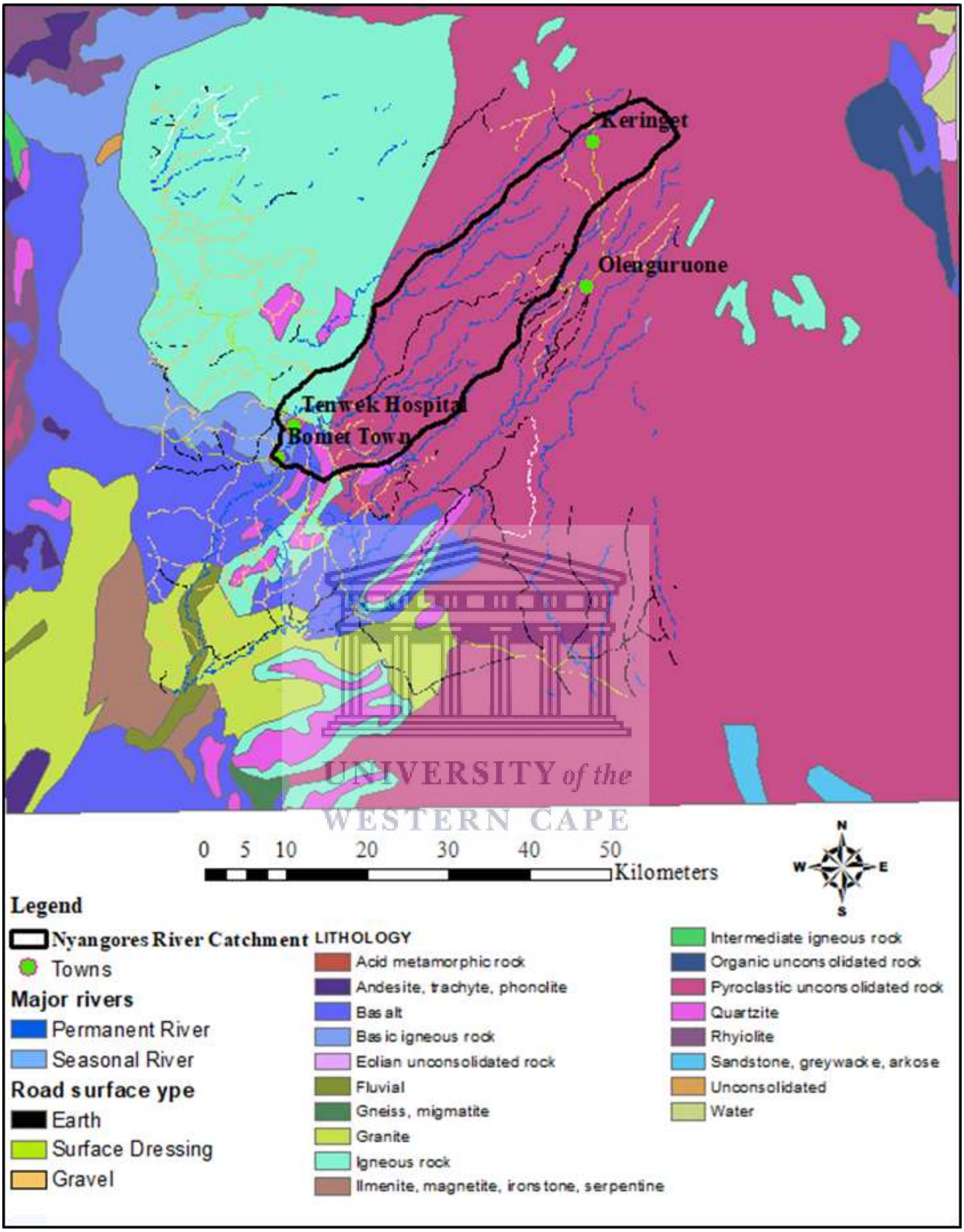

Figure 2.4: Lithological map of the catchment. (Source: ArcGIS 10.2.2 (for desktop © 1999-2014 ESRI Inc.))

2.6 Soils in the catchment

The catchment has different types of soils that vary in texture from sand to clay. The dominant soils are those of Mollic Andosals and other types include Vertic Luvisols, Luvic Phaeozems, Haplic Phaeozems and Humic Cambisols (Figure 2.5). The soils of Andosals in the study area are fertile and support production of tea, vegetables, potatoes and maize (FAO, 2012; Kilonzo, 2014; ISRIC, 2016) ISRIC soils are downloadable from website; https://www.isric.org/. The Vertic Luvisol soils are normally depleted of clays that tends to accumulate in the subsurface layers in the 'argic horizon'. Luvisols soils are porous and well aerated but shallow groundwater may occur in depressions. Luvisols soils are fertile and suitable for agricultural activities with exceptions of those soils with high silt content that makes them susceptible to structural deterioration if tilled in wet conditions or and / or with heavy machinery. Humic Cambisols soils have a loamy to clay soil texture with clay highest in the 'A' horizon. Their good structural stability and high porosity makes them have high water holding capacity. The dystric Cambisols are poor in nutrients hence less fertile and are used for mixed arable farming, grazing and forest land. Luvic Phaeozems soils are mostly leached in wet seasons.

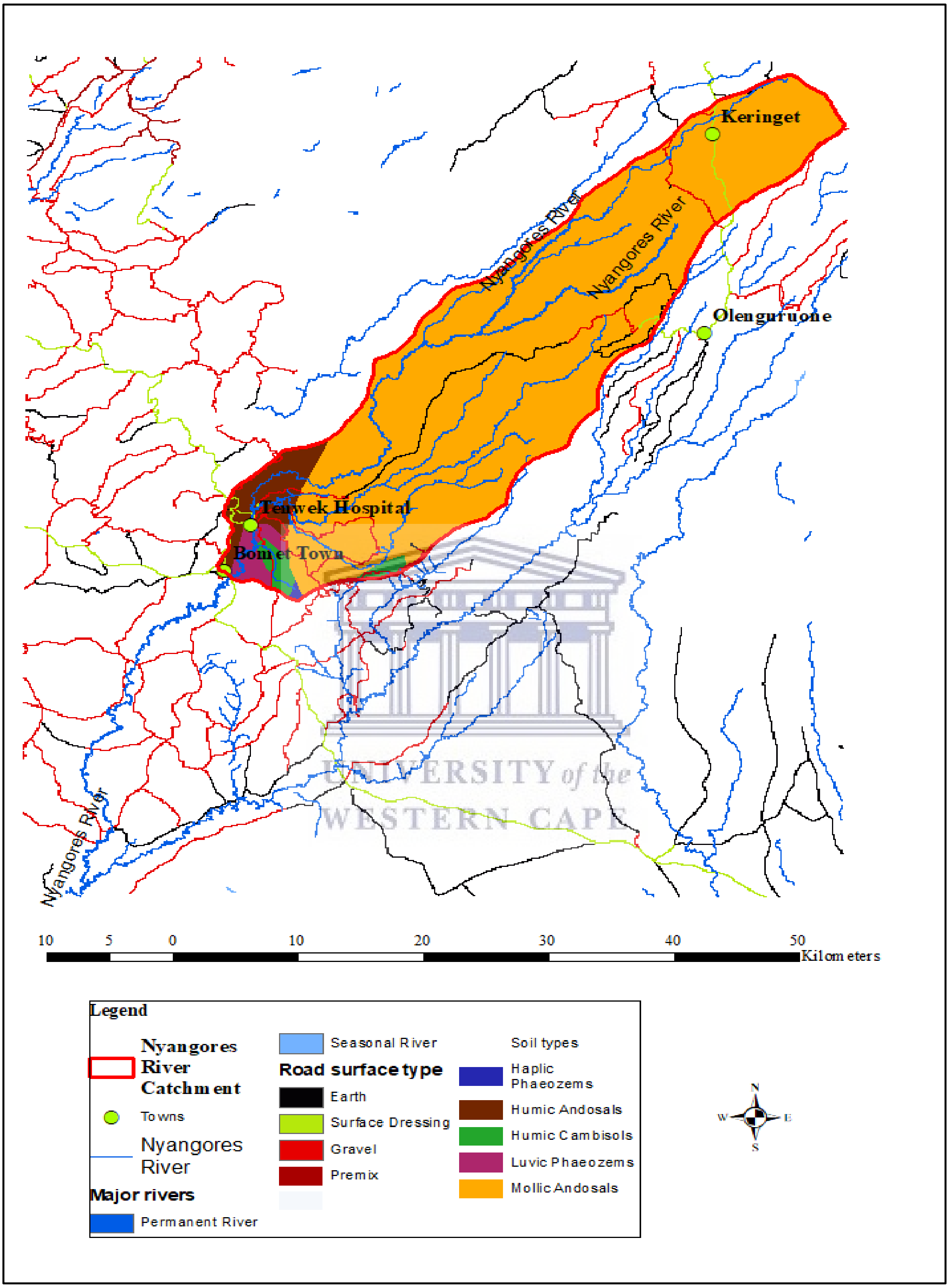

Figure 2.5: Soil classifications in Nyangores River Catchment, (FAO, 2012; ISRIC, 2016). Source: ArcGIS 10.2.2 (for desktop © 1999-2014 ESRI Inc.)

2.7 Vegetation

The middle area of the catchment comprises of indigeneous montane forest with dominant tree species such as *Dombeya guetzenii, Croton macrostachyus, Hagenia abyssinica, and Prunurs africana* (Kinyanjui et. al., 2013). The broad leaved and deciduous trees grow to a height approximately 26 m with over 75% canopy cover (Mutie et. al., 2006). The upper and lower parts of the basin are occupied by grasslands, tea and crops such as maize, beans, potatoes, onions, cabbages, and millet (Figure 2.6).

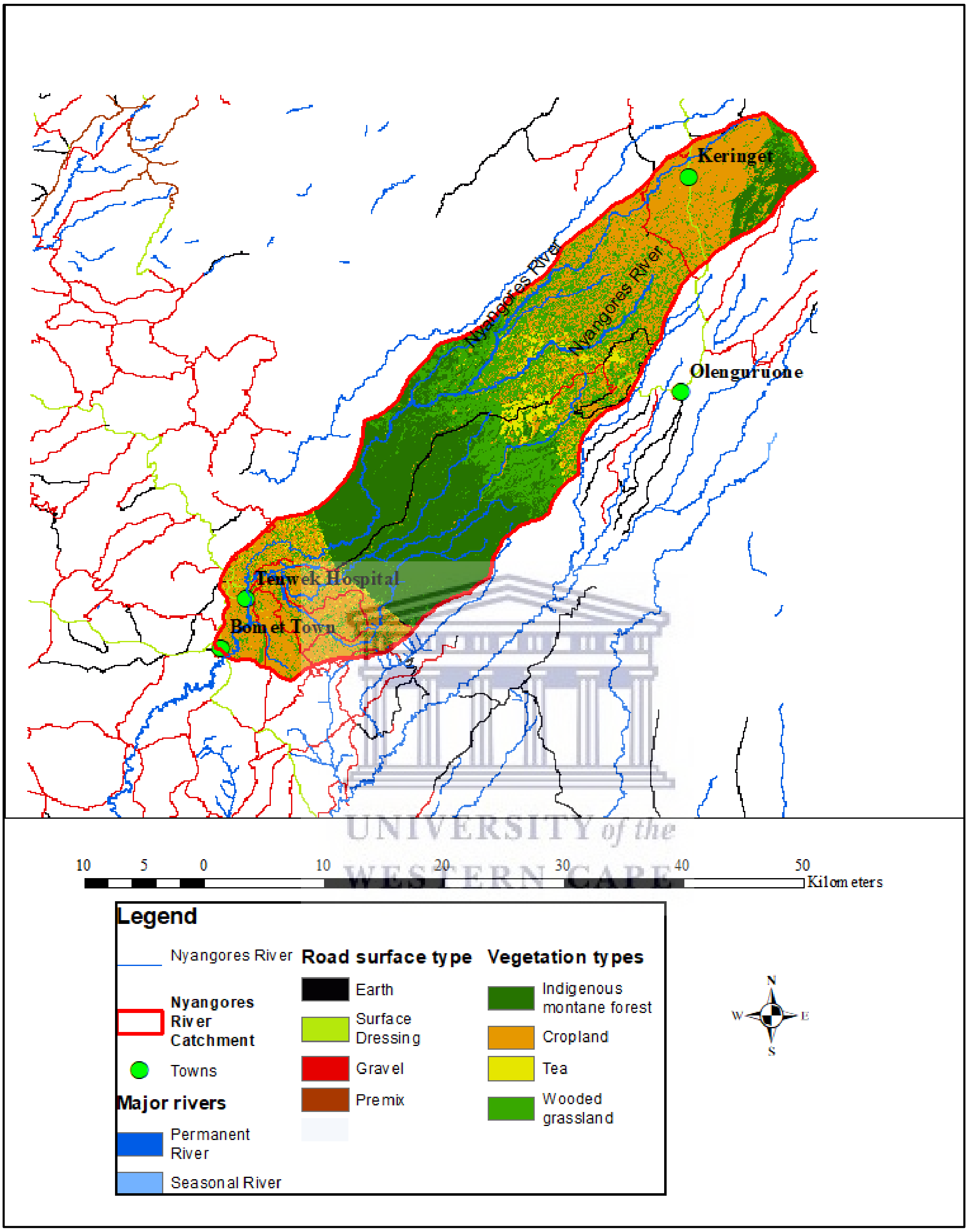

Figure 2.6: Nyangores River Catchment vegetation map. (Source: Land use/cover classification 2015 ArcGIS 10.2.2 (for desktop © 1999-2014 ESRI Inc.))

2.8 Justification of study area

The study area being the headwater of the Mara River Basin has in the past experienced increased population that has led to land use/cover changes that have the ability to change hydrology. The population increase and the land use/cover changes experienced in the catchment (Mati et. al., 2008) forms a good study area to establish the effects of anthropogenic activities on hydrology. This comes at a time when Mango et. al. (2011) highlighted that the flow on the upper reaches of the Mara River (that is Nyangores River Catchment) has become increasingly erratic and water resource managers lack understanding on the sources of flow alteration. This study is undertaken to provide knowledge about whether the expansion of agriculture has given rise to the flow alterations in this catchment. Since the introduction of the "Nyayo Tea Zones" in 1992 initiated by the Kenyan Government to act as forest buffer areas as a means to stop encroachment of forest by the society, and the removal of people from the forest in 2007, there was no more land to extend agriculture even though population continue to increase. This makes it an ideal study area to check the implications of intensified use of limited land on hydrological processes. The Government of Kenya plans to rehabilitate the recently deforested areas occasioned by illegal use of forest materials (Government of Kenya, 2010). This creates the need to investigate the current status of soil water and evapotranspiration so that the intended rehabilitation strategies do not adversely affect the same. The catchment also has adequate data such as rainfall, temperature and river discharge to enable completion of this study.

CHAPTER 3: LAND USE/ COVER CHANGE AND POPULATION DYNAMICS

3.1 Introduction

This chapter investigates how land use/cover in the Nyangores River Catchment have changed over time and the extent to which population dynamics have contributed to these changes. In this chapter it was hypothesised that land use/cover over the Nyangores River Catchment has, over time, been significantly altered due to increased human activities as population increases. The results of this chapter forms the basis of determining the influence of increasing human population on land use intensification (Chapter 4) that has the potential to impact on the hydrological responses of the catchment (Chapter 5 and 6), and may consequently alter the river flow characteristics (Chapter 7).

3.1.1 Land use/cover dynamics

Land use and land cover are terms that are used synonymously in the assessment of land cover changes in river catchments. Land cover refers to the biophysical features that can be spotted on the earth's surface such as deciduous forests, wetlands, grasslands, water etc. (Fonji & Taff, 2014), while land use describes the activities on the land such as residential homes, shopping centres, reservoirs, grazing and many others (Chrysoulakis et. al., 2004; Zubair, 2006). Humans play a key role in changing the environment, causing changes at global and local scales (Paiboonvorachat & Oyana, 2011). Over the last 10,000 years nearly half of the ice-free earth surface has changed as a result of anthropogenic disturbances (Turner et. al., 2008). The use of agricultural and forest goods has made agriculture and forestry to be the greatest transformative land use/cover worldwide (Foley et. al., 2007). According to Nii and Codjoe (2007), the greatest challenge in understanding changes in land cover is to link the behaviour of people to biophysical information at spatial and temporal scales that can aid in decision making. At a global scale, there is a direct relationship between population density and natural resource demand, manifested on land use/cover changes (Meyer & Turner, 1992). For instance, a study of land use/cover dynamics and demographic alteration in southern Burkina Faso showed a strong association between population and land use/cover at all spatial scales. However, at regional scales, only correlations between cropland and forest land were observable (Ouedraogo, 2010). This could be attributed to the fact that at the smaller scales, other variables such as social, economic and political frameworks influence the spatial variation in land use/cover changes. Therefore, it is imperative to consider multiple sources of information and to acquire temporal, spatial and other non-spatial forms of data such as demographic profiles, household characteristics and policies related to land resources administration to be able to understand land use/cover changes.

3.1.2 Assessing land use/cover changes

Information about land use/cover changes is used by policy makers to determine changes in natural resources and evaluation of growth patterns. Today it is assumed that land use/cover changes are a significant part of the environmental alterations with impacts almost equivalent to those of climate change (Weng, 2001; Jensen, 2005; Hassan et. al., 2016). Remote sensing and GIS are important tools in determining land use/cover changes at different spatial scales ((Shalaby & Teteishi, 2007; Twisa et. al., 2019). Many types of satellite images are used for land use/cover change detection with different spatial and temporal resolutions depending on the purpose of such detection (Jensen, 2005). Olang et. al. (2011) highlight that Landsat images have a long history of service and a medium spatial resolution that is adequate to detail changes in a heterogeneous catchment. Various methods have been developed and used to obtain land use/cover changes using satellite images with the most common ones being the pre- and post-classification comparisons (Coppin et. al., 2004; Lu et. al., 2004). The pre-classification comprises techniques which use algebraic thresholds to describe change without effectively indicating the nature of that change and they include the principal component analysis, image differencing and the change vector analysis (Hayes & Sader, 2001; Lu et. al., 2004). Accuracy assessment is an important part of satellite image processing that is commonly used for evaluating a classification performance (Lu & Weng, 2007). Knowing the accuracy of a classified satellite image will improve the confidence of their usage in support of decision making (McIver & Friedl, 2001; Liu et. al., 2004). Data for accuracy assessment (reference data) is usually collected in the field using various methods including simple random sampling, systematic sampling, among others. Two techniques used for accuracy assessment in a classified satellite image are; descriptive and the analytical techniques (Congalton et. al., 1991). Both techniques use an error matrix as the standard way to represent the classification accuracy. The descriptive techniques are commonly used for assessing three types of accuracies; producer's accuracy, user's accuracy and the overall accuracy (Congalton et. al., 1991). The analytical technique is used in estimating the kappa coefficient (Cohen, 1960) which is another measure of accuracy assessment.

After accuracy assessment, post-classification comparison is done. This is a comparison between independently produced classified images. The effectiveness of post-classification comparison lies in the use of data from two dates separately classified in order to eliminate the problem of atmospheric and sensor differences between the two dates (Loveland et. al., 1999). El-Hattab (2016) highlights that the use of post-classification comparison provides both the size and distribution of changed areas (negative or positive) and the percentages of other land classes that share in the land cover change. Post-classification comparisons have provided solutions to detecting land cover changes in catchments with different land use/cover types and can detect the location, nature and rate of land use/cover change (Hardin et. al., 2007; Alphan et. al., 2009; Butt et. al., 2015).

3.1.3 Population dynamics and land use/cover changes

The role of human population in landscape transformation is as a result many factors. These factors include the number of people, level of consumption and the character of material and, energy flows in production and consumption (Meyer & Turner 1992). The human population in Africa has increased by a factor of 4.3 since 1950 (Weil, 2008 as cited in Kaba, 2020). Kenya has equally experienced an increase in population from 15.3 million in 1979 to 47.6 million people in 2019 posing a threat to the allocation of natural resources (KNBS, 2019). The impact of human activities on natural resources has surpassed that of natural change since almost all the global biomes now carry the human footprint (Song et. al., 2018). For instance, Ouedraogo et. al. (2010) observed a population increase between 1976 and 2007 of tenfold that caused a significant land cover change in Ghana. Besides population pressure, land use/cover is also influenced by both the spatial continuity factors and socio-cultural factors (Judex et. al., 2006). Hence, the investigation of the factors influencing land use/cover changes can be supplemented by the consideration of population change patterns. In this regard, changes in land use/cover need to be estimated between time periods when there was significant increase in human population and the associated human activities. Since population size and the rate of growth is a key factor in land use/cover changes, linking land use/cover and population dynamics would provide the patterns of the important variables needed in policy making and decision support (Lambin et. al., 2003).

The Nyangores River Catchment in the sub-humid region of East Africa has experienced rapid population increase over the years due to natural births and migration into this catchment from other heavily populated areas of the country (Lelo, 2005; Mwangi et. al., 2016). The population increase has resulted in rapid land use/cover changes. The land use/cover changes in this catchment resulted mainly from deforestation in favour of agriculture and settlement (Mango et. al., 2011). As it has emerged in other catchments that population increase plays a major role in deforestation (Lambin et. al., 2003; Nii & Codjoe, 2007; Odira et. al., 2010; Berakhi et. al., 2015), the role of population dynamics in land use/ cover changes in Nyangores River Catchment needs to be understood. Studies linking population and land use/cover changes have mainly been done at regional and national scales (Ouedraogo et. al., 2010; Berakhi et. al., 2015) yet changes in land use/cover associated with population changes essentially happens at the catchment level. The study of the influence of population dynamics on land use/cover is important for catchments since the cultural practices of communities in resource consumption is controlled by their socio-economic status and agricultural practices. Such practices are not easily observed at regional or national level.

3.2 Data and Methodology

3.2.1 Land cover data

Landsat images were used to determine land use/cover changes that have taken place in the Nyangores River Catchment over the last 36 years from 1979 to 2015. Landsat images were used since they offer the longest historical information on land use/cover that is suitable for change detection. The medium spatial resolution (30 m) of these images allows detection of changes in land use/cover types in a catchment with heterogeneous vegetation. Landsat images were downloaded using the Global Land Cover Facility (GLCF) website: www.landcover.org and United States Geological Survey (USGS) http://earthexplorer.usgs.gov/. The images for 1979, 1989, 1999, 2009 and 2015 were downloaded in order to coincide with human population census dates for Kenya except for year 2015 whose population was projected. The year 1979 was considered as the base period since this is the time the catchment started experiencing major changes in land use/cover and migration of people into the area (Shivoga et. al., 2007).

The Nyangores River Catchment is covered by two scenes of images on paths 169, 181 and 182 and rows 060 and 061 written as P181R061 and P181R060. The 1999 and 2009 images had strips and shifts respectively, therefore images for 2000 and 2010 were used instead by considering that there is very little change in land use/cover in a span of one year. The 1979 satellite images are in four scenes from two satellites namely Landsat 2 (Multi-Spectral Scanner) MSS on P181R061 and P181R060 and Landsat 3 MSS on P182R061 and P182R060. These images were collected on 15th, 23rd February and 5th March 1979. The 1989, 2000, 2010 and 2015 Landsat images were provided in two scenes by Landsat 4, 7, 5 and 8 respectively (Table 3.1). The images were acquired in February and March because this is a dry season hence easy to differentiate the spectral signatures of forest from those of the crops since the farms have little vegetation.

Table 3.1: Landsat imagery used for this study

Landsat data	Sensor ID	Date acquired	Path/Row	Spatial resolution	Cloud cover (%)
LM21820601979046AAA06	MSS	1979-02-15	P182R060	60 m	0.0
LM21820611979064AAA05	MSS	1979-03-05	P182R061	60 m	0.0
LM31810601979054AAA05	MSS	1979-02-23	P181R060	60 m	0.0
LM31810611979054AAA05	MSS	1979-02-23	P181R061	60 m	0.0
LT41690601989060	TM	1989-03-01	P169R060	30 m	0.0
LT41690611989060	TM	1989-03-01	P169R061	30 m	0.0
p169r060_7dt20000127_z36_10	ETM+	2000-01-27	P169R060	30 m	0.0
p169r061_7dt20000127_z36_10	ETM+	2000-01-27	P169R061	30 m	0.0
L5169060_06020100130	TM	2010-01-30	P169R060	30 m	0.0
L5169061_06020100130	TM	2010-01-30	P169R061	30 m	0.0
LC81690602015044LGN00.tar	OLI-TIRS	2015-02-13	P169R060	30 m	1.5
LC81690612015044LGN00.tar	OLI-TIRS	2015-02-13	P169R061	30 m	1.5

Note: MSS-Multi Spectral Scanner, TM-Thematic Mapper, ETM+ - Enhanced Thematic Mapper Plus, OLI-TIRS-Operational Land Imager and Thermal Infrared Sensor

Classified land use/cover maps for 1990, 2000, 2010, and 2014, obtained from the Department of Resource Surveys and Remote Sensing (DRSRS), Africover and FAO (website: https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/f6fb8562-a595-4c22-961d-b0ce36c4b30f-2008) were used for acquiring the training sites that were used for training the algorithm for image classification.

Selection of land use/cover classes of the study

Land use/cover classes were selected based on Anderson (1976) classification scheme and considering their ability to be impacted on by human activities. For instance, the original land cover was forest and grassland but due to the population increase there was need to find out the relationship between forest shrinkage and change in croplands and built up areas. This is because a change from forest to cropland or built up areas has the potential to alter hydrological processes that is a major concern being addressed in this study. A summary of the land use/cover classes and their selection is provided in (Table 3.2).

Table 3.2: Land use/cover classification scheme

Class name	Description
Forest	Deciduous forest land, evergreen forest land, mixed forest land, orchards
Cropland	Crop fields, pasture, and bare fields
Tea	Tea bushes
Wooded grassland	Consists of various woody shrubs and brushy thickets which occur in dense -to-evergreen and deciduous thickets
Built up	Land areas whose land is covered by structures for instance towns and villages
Bare land	Land areas of exposed soil and barren area such as rocks
Water	River and open water such as ponds

Obtaining reference data from the field

Reference data were collected at the beginning of the research in 2015 using the simple random sampling method as described by Stehman (1992). The advantage of the simple random sampling is the unbiased selection of samples (Congalton, 1986). According to Aronoff (1985) use of random sampling can achieve high overall accuracy because the samples ensures that the most frequent classes are well characterised. The simple random sampling was used in this study due to the ease of getting large samples that were necessary for the detection of land use/cover changes. This study used a group of pixels (3 x 3 pixels) or polygons as the sampling units as recommended by Congalton (2001) because they were easily identified in the field during ground truthing. The ground truth data were collected using a GPS and the Google Earth Images. The Google Earth Images were specifically used to collect ground truth data in areas that were not accessible such as the forest, wooded grassland that were far from the road.

3.2.2 Population and socio-economic data

In order to establish how the dynamics of population influences land use/cover changes in the catchment, several characteristics of the population were required. The population information for 1979, 1989, 1999, 2009 and 2015 for each location (location, being the smallest administrative unit used during census in Kenya) in each district was obtained as secondary data from the Government of Kenya (GOK, 2010). The data obtained for each location included total population, population density, and the number of households. An example of the population information obtained for each year is as shown in Table 3.3 for 2009 (GOK, 2010). The population data for the year 2015 was obtained as projections by GOK (2010). Other supplementary data provided by GOK (2010) was age-groups, net migrated people, employment status, information on materials used for building construction, cooking and lighting fuels for the year 2000 and 2010; Note that 1979 and 1989 population census did not include supplementary data and the population data for 2015 was a projection and hence did not also include supplementary information. Changes in the use of forest resources by households (inform of construction materials and fuelwood) was assessed in order to gain insight on the effects of population and proximity to forest materials on deforestation. Studies indicate that cross proximity of people to the forest increases deforestation (Cohen, 1999; Iqbal et. al., 2012).

The farmers in the catchment have also formed Community Forest Associations (CFAs) whose function is mainly to sensitize communities living near the forest about conservation of the forest for the current and future generations. A focused group discussion with the CFA leaders and other government officials in charge of forest, was held in order to gain insight of the government's and society's challenges in managing the forest resources. The samples for these discussions were obtained purposively and the information received was analysed qualitatively.

Table 3.3: Supplementary data for analyzing influence of population on land use/cover

Category	Data type	Quantity
Population	Total population	Numbers
	Age-group	Numbers
	Density	Persons/km^2
	Households	Numbers
	Net-migration of households	Numbers
Forest materials	Building construction (i.e. roofing and walling)	% households
	Fuelwood	% of households
	Heating	% of households
Land use/cover types	Forest, cropland, grazed and grasslands	Km^2

Note: data for forest, cropland, grazed and wooded grasslands are outputs from image analysis

3.2.3 Image analysis

Pre-processing of satellite images

Landsat satellite images for use in this study were analysed in order to provide the major land use/cover types in the catchment. The main stages of images analysis are summarized in Figure 3.1. In the pre-processing, all images were first rectified to Universal Transverse Mercator (UTM) zone 36S in ArcGIS 10.6.1. Each of the Landsat images were mosaicked since the study area was covered by two tiles of satellite images of Path/Raw of 169/60 and 169/61 and others were 181/60 and 182/61(see Table 3.1). After mosaicking, the sub-setting was done with a rectangular frame covering the Nyangores River Catchment area. The 1979 images were resampled in order to harmonize the cell sizes. Note that the cell sizes for the reflective bands of the MSS Landsat 2 and 3 were 60 m pixels while those of TM, ETM+ and the OLI-TIRS were 30m pixel sizes. The resampling type (interpolation) used was the nearest neighbour since the data had qualitative values.

Supervised classification

Prior to image classification the best bands were selected on the 2015 satellite image based on their ability to provide enough information for the classification. Bands 3,4, and 5 were chosen and a colour composite was prepared. The FAO (2014) an already classified image was used in order to provide the positions of the pure pixels in the colour composite. From the colour composite of 2015, training sites were delineated that were homogeneous for the desired land use/cover classes for this study. The classes included forest, croplands, tea, wooded grassland, built up, bare land and water. The training sites were then used to classify the satellite images of 2015. A supervised classification was used after a site visit to the catchment and identifying the land use/cover types needed. Among the various algorithms used in image classification (including the Parallelepiped Classifier, MINDIST, FISCHER), the maximum likelihood was found to be the most suitable for this study.

Maximum likelihood classifier

The maximum likelihood is a parametric classifier that presumes that there is a normal distribution of each class in all bands where every pixel is assigned to a certain class depending on the probability of belonging to that class (Hagner & Reese, 2007). To illustrate this, the Bayesian formula is used (Sun et. al., 2013). In this equation, suppose there are *G* predefined categories and the unclassified image possesses *m* bands. In this method the classifier quantitatively evaluates both the variance and covariance of the category spectral response patterns when classifying an unknown pixel. In this way it is considered to be among the most accurate classifiers as it is based on statistical parameters (Equation 3.1).

The posterior probability of category *l*, $P\ (G_l/x)$ is defined as.

$$P(G_l/x)\ = \frac{P(x/G_l)P(G_l)}{P(x)} \tag{3.1}$$

Where $P\ (G_l)$ is the prior probability of category *l*, $P\ (x/G_l)$ is conditional probability of observing *x* from G_l (probability density function), $P(x)$ is the probability of observing *x* and similar for each category. If the prior distributions $P\ (G_l)$ is not known, it is assumed that all categories are likely. Therefore, the likelihood function is determined by $P\ (x/G_l)$, which is also called the likelihood of G_l with respect to *x*.

The maximum likelihood classifier has been used severally for satellite image classification with satisfactory results (Alphan et. al., 2009; Butt et. al., 2015; El-Hattab, 2016). The maximum likelihood classifier was carried out on all the images (1979, 1989, 2000, 2010 and 2015). The images were processed using Idrisi Selva version 17.0 (Eastman, 2012), and ArcGIS 10 copyright ©1999-2010 ESRI inc.

Accuracy assessment

Accuracy assessment was carried out using the reference data that was collected in 2015. Prior to reference data collection for this study, the size of samples for each land use/cover type was estimated using the multinomial distribution equation. The multinomial distribution was preferred because the error matrix provides one correct pixel for each class and *n*-1 wrong pixels, where *n* is the number of land use/cover types unlike the binomial distribution which only give right pixels versus the wrong pixels (Story & Congalton, 1986; Baraldi et. al., 2013; Ariza-López et. al., 2019). Again, the multinomial distribution was used to calculate the sample size data that is to be used in constructing the error matrix (Congalton, 1991; Wang et. al., 2016) as shown in Equation (3.2) based on (Tortora, 1978).

The number of samples (n) for each map class or land use/cover type is given by:

$$n = B\pi_i(1-\pi_i)/b_i^2 \tag{3.2}$$

where B is the upper (α/k) x100th percentile of the X^2 distribution with 1 degree of freedom and $\pi_i(i = 1 \ldots., k)$ is the proportion of the population in the i^{th} category, and b is the absolute precision of the sample.

The equation is solved for each of the 'k' category, and 'n' for all categories and subsequently selected proportionately to the size of the category. A 95% confidence level was used in this analysis as recommended by Congalton and Green (2008) while 0.05 was used as the absolute precision. B value was obtained from chi-square table, where X^2 (1, 0.99286) = 7.879. For the map classes whose proportional areas were so small such as the built up, bare land and water, the n values were taken as the minimum sizes (50 samples) Story and Congalton (1986) (Table 3.4).

Table 3.4: Sample size for accuracy assessment for land use/cover classification

No	Land use/cover type	Sample size (n)
1	Forest	691
2	Cropland	744
3	Wooded grassland	109
4	Tea	59
5	Built up	50
6	Bare land	50
7	Water	50

The accuracy assessment was done using an error matrix in Idrisi Selva software using the ERRMAT module (Eastman, 2012). The Landsat image for 2015 was used since reference or ground data was collected in 2015. However, it was not possible to assess the accuracy of the images of 1979, 1989, 2000 and 2010 due to constraints of getting the reference data of these time periods but since the Maximum likelihood classifier was used to classify all the images alike from 1979-2015, it was assumed that the land use/cover areas between the years did not differ significantly. The ERRMAT compares two images for the purpose of accuracy assessment; one image contains the interpreted land use/cover map and the second image contains a map obtained using the ground truth (reference) data that was obtained from the field. The reference data used for accuracy assessment for each land use/cover type depended on the size of the land use/cover (see Table 3.4). The measures of accuracy that were obtained from the error matrix were the overall accuracy, producer's accuracy, user's accuracy and the KAPPA statistic. The overall accuracy according to

Congalton (1991) was computed by dividing the correct pixels i.e. the sum of the major diagonal by the total number of pixels in the error matrix. The producer's accuracy was computed by dividing the total number of correct pixels in a category by the total number of pixels of that category as derived from the reference data i.e. the column data. This measure of accuracy indicates the probability of a reference pixel being correctly classified. The user's accuracy was computed by dividing the total number of correct pixels in a category by the total number of pixels that were classified in that category. User's accuracy indicates the probability that a pixel classified on a map or image actually represents that category on the ground (Story & Congalton, 1986).

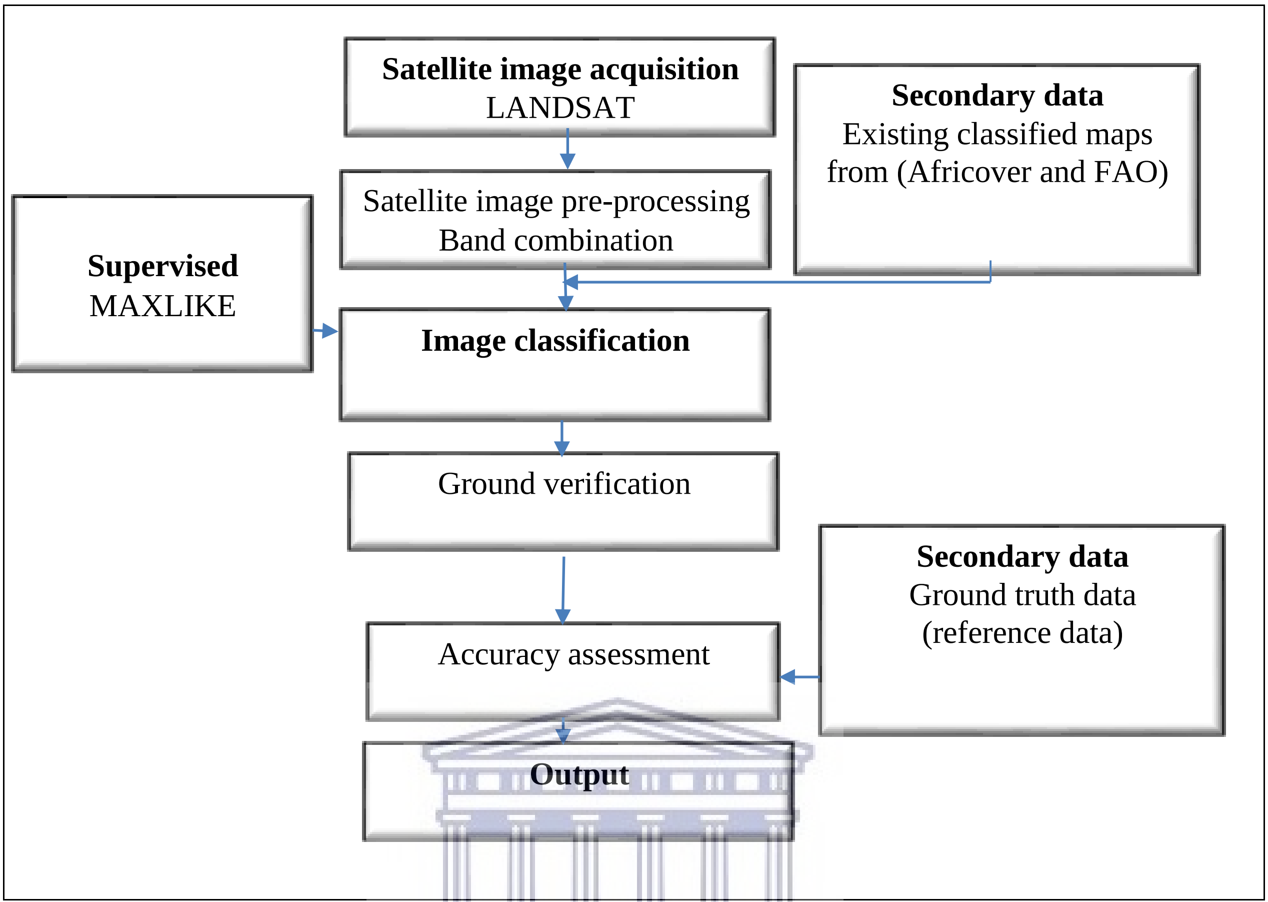

Figure 3.1: The stages of satellite image processing

Land use/cover change detection

This study used the post-classification comparison for change detection using the technique of cross tabulation as proposed by Alphan et. al. (2009). Cross tabulation uses two classified image pairs of successive years in order to determine the quantity of conversions obtained from a particular land cover (Butt et. al., 2015). A two-way cross matrix is then done to detect temporal changes that have occurred between the two images.

3.2.4 Population data analysis

The population data for the Nyangores River Catchment included total population, population density, number of households for each administrative unit (district). Since the population data coincided with the dates when the satellite data was processed, the changes in total population, population density, households as well as consumption of forest materials were estimated by simply subtracting the data from two consecutive periods.

3.2.5 Relating population dynamics and land use/cover changes

The influence of population dynamics on land use/cover changes was done using Pearson correlation. The percentage changes in land use/cover types were correlated with population density using Equation 3.3.

$$R^2 = \frac{\left[\sum_{i=0}^{N}(LC_i - \overline{LC})(PD_i - \overline{PD})\right]^2}{\sum_{i=1}^{N}(LC_i - \overline{LC})^2 \sum_{i=1}^{N}(PD_i - \overline{PD})^2} \quad (3.3)$$

Where R^2 is the coefficient of determination, LC_i and PD_i are the land use/cover change (%) and population density values respectively, $\overline{LC}$ and $\overline{PD}$ are the mean of land use/cover change and population density values respectively, N is the number of observations. The test for the level of significance was computed at 0.05.

3.3 Results

3.3.1 Classified land use/cover maps and statistics

The overall accuracy of the 2015 satellite image was 96.2% and a kappa index of above 0.85 (Table 3.5). Note that a kappa index above 0.8 signifies a strong or good agreement of the classified image and the ground truth image. The satellite images after processing were found to have four main land use/cover types namely forest, cropland, tea and wooded grassland and minor ones covering the built up, bare land and water (Figure 3.2). From the images the forest cover was observed to progressively diminish between 1979 and 2015 while cropland increased progressively within the same time.

Table 3.5: Accuracy assessment of land use/cover changes for Landsat satellite images of 2015

Land use/cover type	Producer's accuracy	User's accuracy
Forest	96.8	97.6
Cropland	91.5	90.2
Tea	94.9	97.2
Wooded grassland	88.6	87.4
Built up	78.6	80.2
Bare land	82.6	81.7
Water	80.2	79.8
Overall accuracy	96.2	
Kappa statistic	85.7	

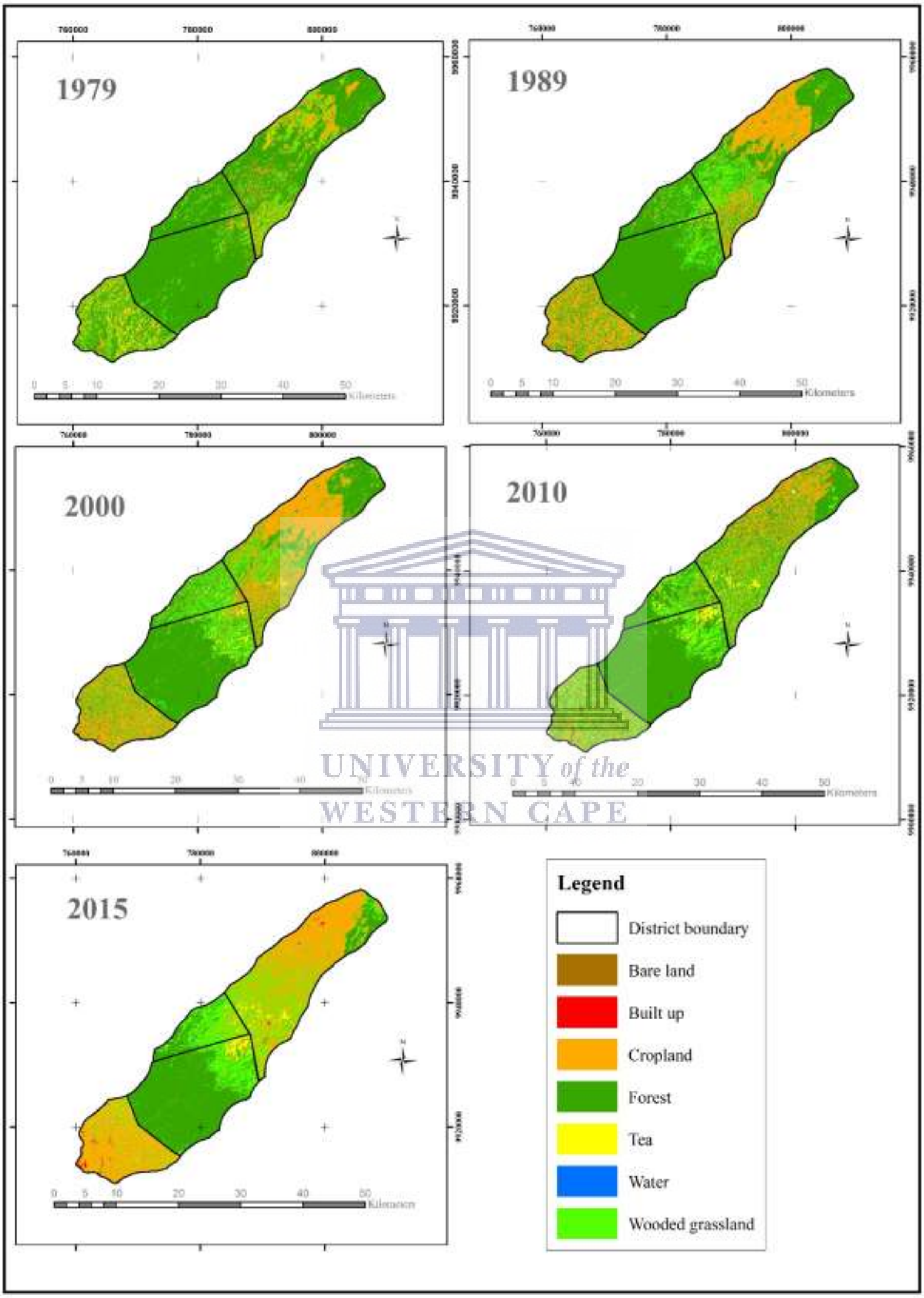

Figure 3.2: The land use/cover types in the Nyangores River Catchment for the periods 1979, 1989, 2000, 2010 and 2015

On further analysis the results indicate that 72% of the catchment area was covered by forest in 1979 and only 14% of the catchment area was covered by cropland. There was a conspicuous decrease in the area covered by forest between 1979 and 2015 of approximately 292.5 km^2 (55%) while cropland area increased by more than double its original area (169 %). The area under wooded grassland also doubled over the same period (Table 3.6).

Table 3.6: Land use/cover classes and areas in km^2 (1979-2015)

	Year									
	1979		1989		2000		2010		2015	
Land use/cover	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Forest	531.9	72.2	442.8	60.1	361.9	49.1	421.5	57.2	239.4	32.5
Cropland	104.8	14.2	188.3	25.6	225.3	30.6	132.3	18.0	282.0	38.3
Tea	9.3	1.3	9.9	1.4	27.3	3.7	43.7	5.9	27.6	3.6
Wooded grassland	89.9	12.2	94.6	12.8	120.9	16.4	135.8	18.4	182.8	24.9
Built up	0.0	0.0	0.3	0.0	0.4	0.1	1.4	0.2	2.0	0.3
Bare land	0.9	0.1	0.7	0.1	0.9	0.1	2.0	0.2	2.4	0.3
Water	0.2	0.0	0.4	0.0	0.3	0.0	0.3	0.1	0.8	0.1
Total area	737	100	737	100	737	100	737	100	737	100

3.3.2 Land use/cover change detection

In order to determine the nature of change of different land use/cover classes or the shift in the land use/cover classes, cross-tabulation of the images was done. The results showed that, over the four decades, there was increase in cropland, tea, and wooded grassland at the expense of the forest land. For instance, the forest cover changed from 531.9 km^2 to 442.6 km^2 representing a 16.7% decrease in the area between 1979 and 1989; cropland increased from 104.7 km^2 to 188.6 km^2 representing 80.1% increase over the same time. The change in cropland was mainly contributed by forest (77.1 km^2) and wooded grassland (43.2 km^2) (Table 3.7). Note that for the whole period (1979-2015), 179.5 km^2 of the forest cover was converted to cropland while 105.8 km^2 of the same forest cover was converted to wooded grasslands (adding up to a loss of 285.3 km^2 of forest cover) an equivalent of 53.6% of the forest area; only about 2.6 % of the forest was converted to the other land use/cover types (Table 3.8).

Table 3.7: Cross-tabulation of land use/cover classes between 1979 and 1989 (area in km²)

	Forest	Cropland	Tea	Wooded grassland	Built up	Bare land	Water	1979
Forest	381.3	77.1	4.43	68.99	0.00	0.114	0.034	531.97
Cropland	27.41	60.64	2.25	14.21	0.085	0.127	0.039	104.76
Tea	1.36	7.32	0.45	0.22	0.00	0.00	9.36	9.36
Wooded grassland	32.48	43.25	2.79	11.16	0.12	0.00	0.03	89.83
Built up	0.00	0.00	0.00	0.00	0.02	0.10	0.00	0.12
Bare land	0.06	0.32	0.00	0.03	0.02	0.42	0.00	0.85
Water	0.02	0.01	0.00	0.00	0.00	0.00	0.08	0.11
1989	442.63	188.64	9.93	94.61	0.24	0.76	0.19	737.00

Table 3.8: Cross-tabulation of land use/cover classes between 1979 and 2015 (area in km²)

	Forest	Cropland	Tea	Wooded grassland	Built up	Bare land	Water	1979
Forest	232.40	179.50	11.50	105.80	1.00	1.20	0.13	531.53
Cropland	3.50	50.40	7.50	42.00	0.40	0.50	0.04	104.34
Tea	0.00	0.10	4.00	6.00	0.20	0.00	0.00	10.30
Wooded grassland	3.80	52.40	4.00	28.90	0.40	0.40	0.03	89.93
Built up	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01
Bare land	0.03	0.23	0.00	0.20	0.00	0.20	0.00	0.66
Water	0.01	0.12	0.00	0.00	0.00	0.00	0.10	0.23
2015	239.7	282.8	27.0	182.9	2.00	2.30	0.30	737.00

The increase in cropland at the expense of forest and wooded grassland between 1979 and 1989 could be attributed to the increase in population mainly due to migrations from other parts of the country to the catchment. A summary of the entire image indicate that more forest cover was converted to cropland and wooded grassland between 1979 and 2015. However, between 2000 and 2010, the forest cover increased and croplands decreased (see Table 3.6). This change was attributed to the removal of people from the forest following government directive and to a lesser extent the migration of people out of the catchment following political unrest between communities.

3.3.3 Changes in total population between 1979 and 2015

The total population in the catchment increased continually at the rate of 9.7% per year from 1979 to 2009 resulting in an increase of 291% and consequently an increase in population density from 47 inhabitants /km^2 in 1979 to 184 inhabitants /km^2 in 2009. Similarly, the number of households increased from 6,268 in 1979 to 26,918 by 2009; a percentage increase of 329%. The projected population from 2009 to 2015 also showed an increasing trend (Table 3.9).

Table 3.9: Population of Nyangores River Catchment by districts from 1979-2015

District	Total area (km2)	1979			1989			1999			2009			2015
		Population	Density (inhab/km2)	Households	Population	Density (inhab/km2)	Households	Population	Density (inhab/km2)	Households	Population	Density (inhab/km2)	Households	Population
Nakuru	286	4994	17	3320	23323	81	4270	35380	123	7543	61803	216	13302	89781
Bomet	131	29212	223	4950	58017	442	7695	68183	520	9844	72789	555	13427	98304
Narok	241	528	2	87	922	3	170	1075	4	180	1450	6	189	1780
Buret	79	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	737	34734	47	6268	82262	112	12136	104638	141	17567	136042	184	26918	189865

Considering the population changes in the catchment per decade, each of the four districts had population increase in each decade. For instance, Nakuru had the highest increase in population between 1979 and 1989 (367%). This population translated to an increase in households by 29% and an increase in population density by 376%. The population increase per decade for the entire catchment is as shown in Table 3.10. The results showed that 1979-1989 was the period when the catchment experienced high population increase that could be attributed to natural births and migration of people into the catchment. Note that Buret District is uninhabited since the district is mainly forested.

Table 3.10: Decadal percentage changes in population, population density and households from 1979-2015

District	Total area (km2)	Change 1979-1989 (%)			Change 1989-1999 (%)			Change 1999-2009 (%)			Change 2009-2015 (%)
		Population	Density	Households	Population	Density	Households	Population	Density	Households	Population
Nakuru	286	367	376	29	52	52	77	75	76	76	45
Bomet	131	99	98	55	18	18	28	7	7	36	35
Narok	241	75	50	95	17	33	6	35	50	5	23
Buret	79	-	-	-	-	-	-	-	-	-	-
Total	737	137	138	94	27	26	45	30	30	53	40

When the total population was distributed into age-groups across the districts (the age groups were categorised according to the census data) the highest increase was for the age-group between 15-64 years. The proportion of the people in this age-group in all the districts was more than 45% of the total population. The age-group between 5-14 years also registered more than 25% of the total population. The age-group of 0-4 years was only 15% of the population in all the districts. The high population of the 15-64 age-group has implications to land use/cover changes in a catchment. This is because the group has the most economically active people who are likely to interact more with the resources that will impact on the land cover (Figure 3.3).

Figure 3.3: Proportion of population in age-groups in the districts of Nyangores River Catchment.

The increase of population in the Nyangores River Catchment through births and migration shows that Nakuru District had the highest immigrants attributable to its proximity to the cosmopolitan city of Nakuru followed by Narok District. Bomet District had the lowest migrants. However, it was noted that migration into Nakuru and Narok Districts was minimal in 2009. This could be attributed to migration of people out of the districts following political unrest in 2007/2008 (Figure 3.4). The migration of people into the districts could be associated with the observed changes of land cover observed in Section 3.3.1.

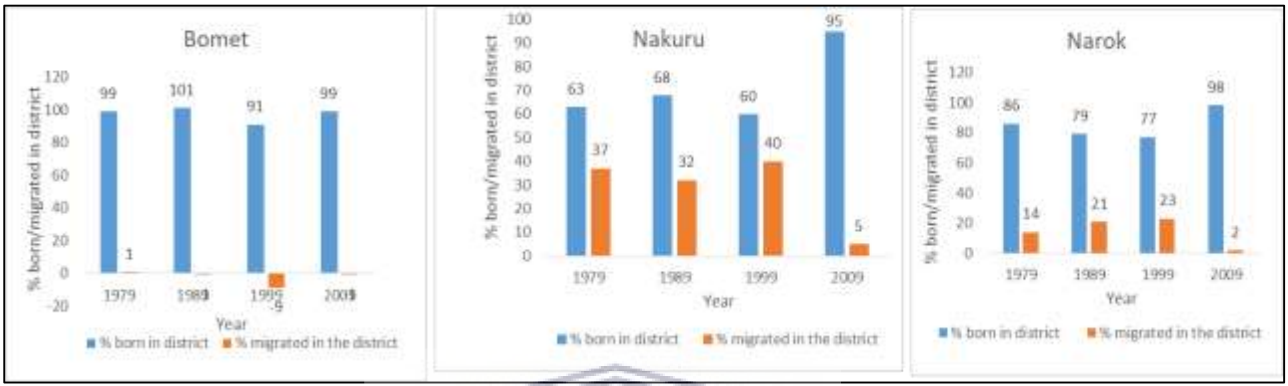

Figure 3.4: Proportion of people born and migrated into the districts in each decade between 1979-2009

The employment status of the people in the study area indicates that on average 20-25% worked in family farms particularly the economically active group (15-64 years). The percentage of people with formal employment (worked for pay) depends on the locality; for instance, in Nakuru District there was a higher percentage of formerly employed people compared to other districts which could be attributed to the close proximity to the cosmopolitan city of Nakuru (Figure 3.5). The relatively large number of people working in farms (above 20%) would imply an increase in farming activities that have the potential to alter hydrological processes in the catchment.

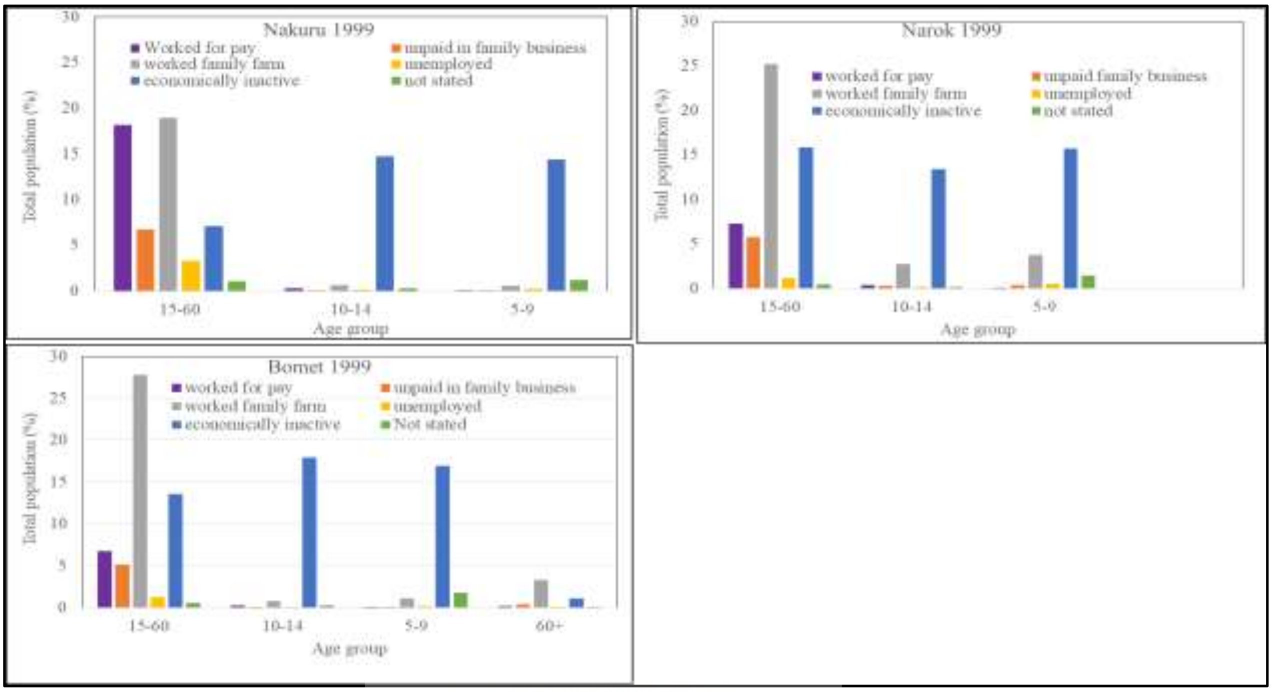

Figure 3.5: Employment status of people in different districts. Worked for pay- indicates the proportion of people with formal employment

3.3.4 Use of forest resources

People in the catchment currently interact with forest mainly through the use of materials for purposes including construction (houses, sheds, fence etc.), fuelwood and charcoal. The change (in percentage) in forest materials use for some locations within Nakuru and Bomet Districts for the decade between 2000 and 2010 are shown in (Table 3.11). The use of forest materials can be related to the proximity to the forest and to a lesser extent the number of households. For instance, the consumption of fuelwood and charcoal is highest in locations with more households and close to the forest (e.g. Tinet, Kiptagich and Kiromwok) while locations that are far from the forest use less fuelwood despite having many households (e.g. Chebara, Merigi and Bomet Township) (Figure 3.6). Note that even though the number of people is a contributing factor to consumption of forest materials, proximity of households to the forest is a more important factor. The consumption of forest materials is evidenced by photographs of women who fetch fuelwood for domestic use in the nearby forest Figure 3.7 a, and tree logs fetched for use in nearby tea factories Figure 3.7b.

Table 3.11: Change of households (in %) and the use of forest materials in Nakuru and Bomet locations between 2000 and 2010 source: GOK 2010, 2000-2010 census

Location Name	Change (%) in households 2000-2010	Change (%) in use of forest materials 2000 to 2010			
		Mud/wood	Wood only	Fuelwood	Charcoal
Ndaraweta	6.1	4.3	5.0	6.6	1.9
Mugango	27.8	11.6	7.7	27.0	3.2
Kiromwok	**31.7**	**10.1**	**10.3**	**31.1**	**4.3**
Merigi	**68.5**	**39.4**	**13.8**	**6.5**	**6.1**
Bomet Township	50.5	20.2	14.5	49.1	6.1
Tinet	**110.7**	**84.1**	**33.4**	**61.4**	**65.1**
Sinendet	6.7	0.8	17.1	8.4	2.2
Kiptagich	**57.9**	**57.0**	**59.6**	**77.1**	**47.5**
Kipsonoi	17.9	3.4	21.5	10.6	16.0
Chebara	**73.1**	**18.9**	**22.6**	**23.6**	**15.2**
Keringet Nakuru	6.3	62.5	44.6	3.5	3.8
Marishoni	15.2	4.8	2.2	7.4	0.6

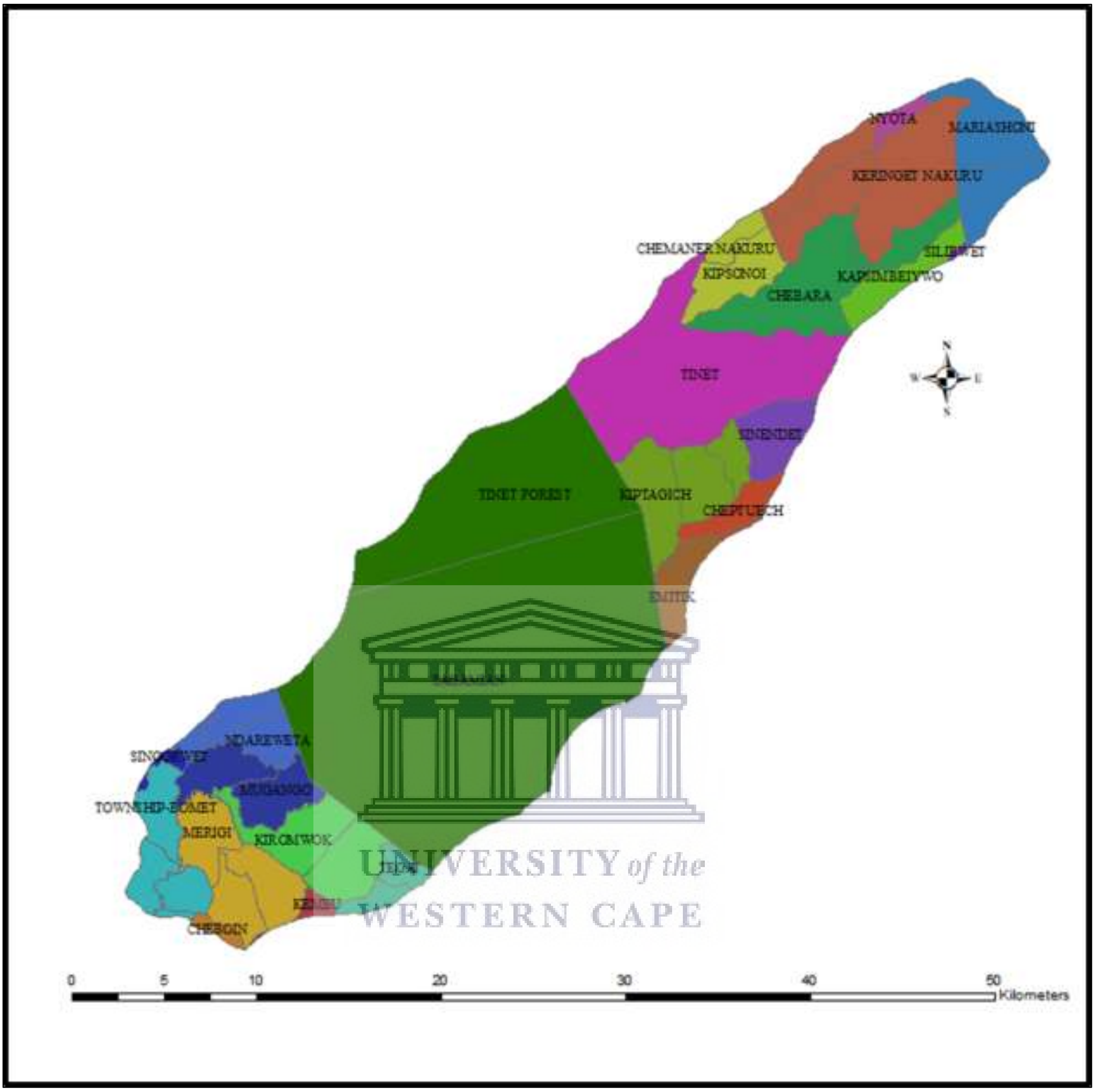

Figure 3.6: Names of locations in relation to the forest; note, Tinet, Kiptagich and Kiromwok locations with close proximity while Chebara and Merigi are far away from the forest.

Figure 3.7: Consumption of forest materials (a) women carrying fuelwood from the nearby forest (b) wood stacked for a nearby tea factory. Source: photographs by the author

Results for the use of forest materials showed that more than 40% of the people in Bomet, Nakuru and Narok Districts used wood for construction. Fuelwood and charcoal were the most commonly used cooking fuels in these districts with fuelwood being used by at least 50% of the households (Figure 3.8). Such high consumption of forest materials are the possible causes of forest degradation in this catchment even after forest encroachment was stopped by government.

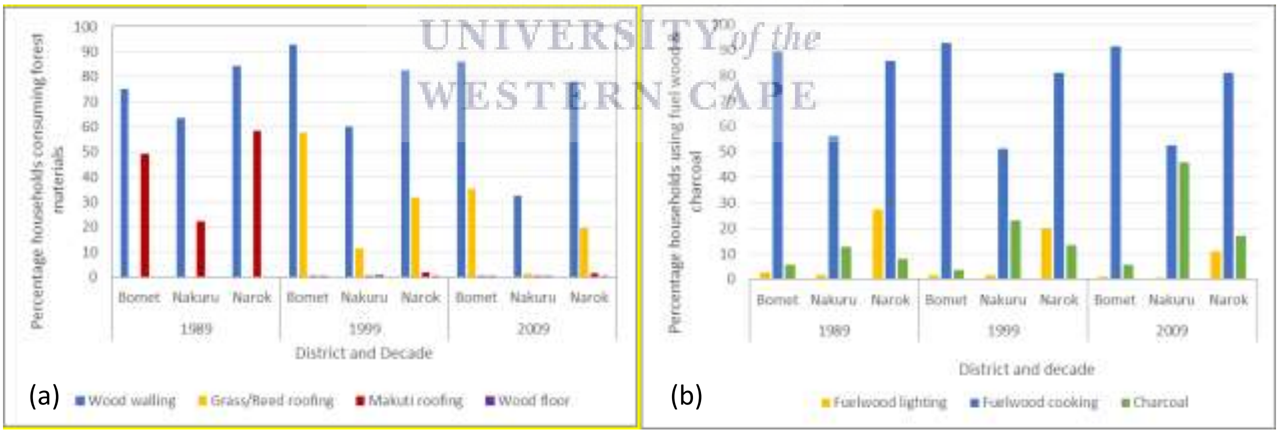

Figure 3.8: Percentages of households using forest materials for; (a) building (b) fuel

The overall observation was that population growth increased use of wooded construction materials, expansion of croplands, and consequently decreased the area under forest. Increasing number of households resulted in the expansion of the built up areas hence reducing the available cropland. The wooded grassland increased as population increased due to use of forest material by the local community and clearing of forest for logs and charcoal. The forest area left after illegal cutting of trees was not necessarily put into cropland but became wooded grassland.

3.3.5 Correlation of population density and land cover changes

Pearson correlation using five points data analysis showed that change in land cover was associated with population increase. For instance, at the catchment scale, there was a strong correlation between population and change in areas of forest ($r = -0.85$; $p<0.05$), wooded grassland ($r= 0.9$; $p<0.05$), and water ($r= 0.75$; $p<0.05$) (Table 3.12). However, the correlation of population with land covered by tea was not significant. The negative correlation between forest cover and population density implies that as people increased land cover diminished as people converted forest to cropland as was indicated in section 3.3.1.

Table 3.12: Correlation between population density and land use/cover changes in (%) from 1979 to 2010

	Population density/Land use/cover type						
	Forest	Cropland	Wooded grassland	Tea	Built up	Bare land	Water
r	-0.85*	0.45	0.9*	0.42	0.03	0.133	0.75*
P-value	0.029	0.149	0.021	0.475	0.382	0.171	0.029

Note: *means the correlation is significant at p<0.05; r is the correlation coefficient

3.3.6 Measures to curb further forest destruction

From a focused group discussion with the Community Forest Associations (CFA's) the main socio-economic activities that have influenced tree cutting include illegal logging for timber and charcoal burning, fuelwood collection, poles and posts for house construction and fencing. The government has however put measures in place to curb tree cutting. The farmers have also formed CFA's to sensitize communities living near the forest about conservation of the forest for the current and future generations. Although the government is committed to protecting the forest from destruction by communities, there are numerous challenges. For instance, from the focused group discussions, the forest officers indicated that they do not have enough manpower and patrol vehicles to man the whole forest (of 13,400 ha). The forest rangers are supposed to protect timber theft, trespass, wild fire, and collect levy on forest produce. In terms of technology the rangers use a global positioning system (GPS) and phone cameras to collect evidence of people destroying the forests and to mark the particular area of crime. So what came out strongly is that the government has challenges in employing enough workers and/or providing means of patrolling the forest such as vehicles and motorbikes. It also came out strongly that after people are caught destroying the forest they are rarely prosecuted.

3.4 Discussion

The results obtained in this Chapter, show that between 1979 and 2015, forested area shrank by 55%. The forest area was mainly converted to cropland and wooded grassland. This loss of forest cover is far above the global forest shrinkage of 33% (FAO, 2016). The high rate of shrinkage of forest cover was attributed to the demand for human settlement and the need to boost food production in rural areas where the livelihoods mainly depend on subsistence farming. These findings are in line with other studies done in rural Kenya; for instance, Ulrich et. al. (2012) indicate that communities' livelihoods are mainly anchored on farming while Baldyga et. al. (2008) highlight that changes of land use/cover were a result of small scale agriculture for food production and pastures in Njoro River watershed. These results are consistent with the global trends that indicate that 33% of forest loss is due to subsistence agriculture particularly in low income countries where rural population is growing fast (FAO, 2016). Further, the results indicate that the annual rate of forest cover loss (at 8.15%) in Nyangores River Catchment, was quite high compared to the annual rate of forest cover loss of 0.35% in Kenya between 1990 and 2010 as indicated by FAO (2010) and Recha et. al. (2012). The results are consistent with those of Mati et. al. (2008) who noted a decrease of forest cover by 32% between 1973 and 2000 in the wider Mara Basin of which Nyangores River Catchment is the upper part.

The results on population indicated that there was a high rate of increase (9.7% per year) particularly between 1979 and 2009. The growth in population was as a result of both natural births and migration of people from the heavily populated areas of Central and Western regions of Kenya (Spruyt, 2011; Muthoni et. al., 2013). The increase in population resulted in increased human activities that greatly contributed to the loss of forest cover. For example, the loss of forest cover to croplands was particularly high within the period between 1979 and 1989 when there was a large number of immigrants into the catchment. Geist and Lambin (2002) perceived migration as a key demographic factor affecting the spatial and temporal land use/cover change. Kashaigili and Majaliwa (2013) also found that due to the large influx of refugees in Malagarasi River Catchment in Tanzania, the cultivated and wood lands increased significantly while wetlands decreased.

Due to the high population growth and due to the high proportion of the economically active group (15-64 years), there was a sharp rise in the number of households in the catchment which consequently resulted in increased conversion of forest to croplands and consumption of forest materials (mainly fuelwood and building). Axinn and Ghimire (2011) also observed that in Chitwan

Valley in Nepal people in the economically active age group create more households through marriage and children bearing. The social-economic activities of this age-group increase consumption of forest materials through construction of buildings, and energy use hence reducing the land allocated for agriculture. The expansion of cropland area was also necessitated by the need to increase diversification in crops to improve food production. Commercial crops such as tea were introduced in order to reduce dependence on food crops and to improve social-economic status as indicated by Kiprono (2012).

Proximity to the forest together with increase in population influences consumption of forest materials. The data analysed revealed that the majority of the households and tea factories use fuelwood and charcoal as the main fuel for cooking, warming and lighting the houses. Proximity to the forest was observed to be associated with increased use of forest materials. FAO (2010) highlighted that households living within 5 km from the forest use forest resources for their needs therefore compromising forest conservation efforts. The findings of this study are in line with the observations made by Hosonuma et. al. (2012) who noted that fuelwood collection, timber extraction and logging, cultivation and grazing are major causes of deforestation in Africa. These findings are also consistent with studies of (Knight and Rosa, 2012; Rotich and Ojwang, 2021) who observed a significant negative effect of population on fuelwood consumption in developing countries.

The Government of Kenya's effort to conserve forests and stop human encroachment in the Nyangores River Catchment started from the early 1990s (African Development Fund, 2002). Particularly this was done through the introduction of the 'Nyayo Tea Zones' in 1992 whose aim was to create a buffer zone separating farms and the forest area. However, the cutting of trees in the buffer zone area also increased cropland at the expense of forest. In 2009, the government evicted illegal immigrants who had settled in the forest area (Spruyt, 2011; Mutugi & Kiiru, 2015) with resultant increase in wooded grassland. Furthermore, illegal logging for building materials and charcoal burning together with high reliance on forest materials for energy continued to put demand on the forest thus resulting in the creation of more wooded grasslands in the forest. The Landsat images indicated an increase in wooded grassland between 2010 and 2015 probably due to increased illegal timber logging thus introducing more grassland parches in the forest. Furthermore, even where the government has tried to put in measures to increase forest cover through evictions from the forest and tree planting, lack of enough resources needed to comprehensively conserve forests compromise the gains made (Odira et. al., 2010; Onyango et. al., 2013). Therefore, enforcement of the laws on forest destruction and increased resources for forest conservation are needed in Kenya in order to improve forest cover and consequently enhance the water cycle in catchments.

3.5 Summary

The aim of this Chapter was to investigate how land use/cover in Nyangores River Catchment has changed over time, and how population dynamics have contributed to these changes. Using interpretation of satellite images, it was evidenced that there are significant changes in land use/cover in the catchment. Much of the temporal and spatial variability in land use/cover changes occurred through the conversion of forest cover to cropland that surpassed the global forest loss. The key factors that influenced these changes were the increased human population and the associated activities particularly in the productive age of 15-64 years. Proximity to the forest was another factor influencing forest reduction through mainly wood consumption. The government policies to conserve forest controlled clearing of forest for settlements and farming. However poor enforcement of forest laws has led to the increase of wooded grasslands in the forest due to illegal logging. The changes in land use/cover of the magnitudes such as that observed in Nyangores River Catchment has the potential of altering the hydrological systems in a catchment. However, forest protection is on the other hand likely to introduce intensification of use of the available agricultural land; this has the potential to alter rainfall partitioning in a catchment. The results of this Chapter forms a basis of investigating how the available agricultural land is intensively used and how the intensified use of land is likely to influence the hydrology of this catchment. The next Chapter explores the nature of land use intensification being practiced in this catchment as population increased.

CHAPTER 4: INTENSIFICATION OF LAND USE AND ITS DRIVING FACTORS

4.1 Introduction

The aim of this Chapter was to determine the nature of intensification of land use within the Nyangores River Catchment and, examine the main factors driving it. In this chapter it was hypothesized that population increase and lack of available land for expansion (observed in chapter 3), have resulted to land use intensification to cater for the increasing population. Land use intensification can affect the soil properties and consequently may alter hydrological processes in a catchment. The results of this chapter forms a basis for the investigation of effects of land use/cover changes on hydrological processes discussed later in Chapter 5&6.

4.1.1 Land use intensity

Land use is intensified through the introduction of new farming technologies including increased use of improved farm inputs and mechanization. Intensification of land use can be traced through the way farming methods have evolved over time mainly driven by the world's endeavours to produce enough food for the growing population (Nambiro, 2007; Oyekale & Adepoju, 2012).

Many methods are used to evaluate land use intensity. These methods include the use of production intensity, cropping frequency, inputs or application of materials, labour skill and technology (Leaf 1987). However, some of these methods have limitations. For instance, the use calories produced by certain foods to determine production intensity is difficult because farmers grow different crops throughout the year that may differ in calories (Shriar, 2000). The use of the cropping system according to Netting (1993) as cited in Shriar (2000) is applicable if farmers are using similar technologies while the use of inputs such as fertilizer depends on the nature of farming as well as the nature of the soils. Therefore, the method that is commonly used in evaluation of land use intensity is the R-value proposed by Ruthenberg (1976). The R-value is calculated as the area under cultivation as a proportion of the farm unit relative to the whole available arable land (Nambiro, 2007; Alawode et. al., 2016). On the other hand, land use intensity may be manifested in reduced production cycle as well as increased cropping frequency per year. However, the more land under cultivation is intensified the more the soil is prone to degradation (Kehoe et. al., 2015). This may influence the hydrology of a catchment (Nambiro, 2007).

The most common reasons for land degradation is the reduction of fallow land and the shortening of time that land under cultivation is left fallow. Fallow period is the time the land is not occupied by crops (for at least a couple of years) and it is a labour saving technique for restoring soil fertility (Otsuka, 2001). Continuous cultivation of land impacts negatively on the physical, chemical and biological properties of the soils (Yimer et. al., 2008; Abrol & Sharma, 2012; Karuma et. al., 2014; Alvarez & Steinbach, 2019). Cropping systems influence land use intensity by the way a farm is occupied with a certain crop. For instance, Okike et. al. (2001) observed that farmers in Northern Nigeria had an average of 17 cycles of continuous cropping before leaving land fallow for a short period of time. They also noted that farmers not only cultivated continuously but also subjected the land to double or triple cropping; a situation that led to high land use intensity. Nambiro (2007) found that increased intercropping and multiple cropping in a plot of land increased the land use intensity. The choice of crops, mainly driven by markets, influences land use intensity by increasing the area under cultivation. For instance, Nambiro (2007) found that in Kakamega (Kenya) the sugarcane areas increased between 1982 and 2004 due to the introduction of Mumias sugar factory. Since land use in a country is subject to government policies that regulates prices of farm inputs, incentives to farmers and availability of markets for farm produce (Pender, 2006), land use practices cannot be replicated in all situations.

The negative effects on soil properties during continuous cultivation emanate mainly from the way the soil is disturbed by different tilling methods. Soil tilling methods have continuously changed over time from simple hand tilling to complex mechanization. The improved tillage methods are usually employed in land use intensification to boost food production and catchment management (Karuma et. al., 2014). Tillage methods usually practised depend on the type of soils, climate, socio-economic status, type of crops etc. These methods include no-till and tilling using various implements such as animal traction, mould board, tractor drawn disc ploughs and harrows, etc (Biamah, 2005). Various studies have related the effects of tilling practices on hydrological processes (Minas & Frank, 2001; De Cárcer et. al., 2019). For instance, Mujdeci et. al. (2010) studying the effects of different tilling methods reported that the chisel ploughing combined with harrowing led to an increase in soil moisture loss at Suleyman Demirel University (Turkey) research farm. Karuma et. al. (2014) observed that the ox-drawn ploughing retained soil water more than other ploughing methods including the disc ploughing and harrowing in Mwala District (Kenya).
Tilling methods have also been observed to have effects on soil properties. For instance, Li et. al. (2007) reported that, after 6 years the surface soil bulk density was significantly lower under conventional tillage than no tillage in Northern China. Alvarez and Steinbach (2019) reported that the no tillage practice had a mean of 13-14% more water root zone than tilled soils in Argentina.

4.2 Socio-economic factors influencing land use intensification

The social-economic factors that drive land use intensifications are many and varied. As theorized by Boserup (1981), population growth and scarcity of land has led to reduced fallow land in favour of continuous cropping. This is especially for land areas near forest frontiers where land extension into forests have been prohibited by governments in favor of increasing forest cover for environmental conservation. For instance, the closure of Kakamega forest frontier in Kenya led farmers to reduce former fallow land areas and shortened the fallow periods to cope with crop production (Nambiro, 2007). Bourke (2002) observed that as population increased by more than 50%, the increase of available land for cultivation was only by 10% in Papua New Guinea. The slow increase of land for cultivation in Papua led to land use intensification through shortening of fallows to enable introduction of new crops and longer cropping periods.

Land use decisions are determined mainly by both macro (land policies, markets and trade), and micro level processes (such as human and economic endowment of the household) (Shriar, 2000). While the effects of macro-level processes on land use are known (Turner et. al., 1995, as cited in Bergeron and Pender, 1999), little is understood on the influence of the micro-level processes on land use particularly in the Nyangores River Catchment.

In Chapter 3 of this thesis it was observed that rapid population increase and the associated activities had significant influence on land cover changes. It is therefore important to understand how the socio-economic factors influence the intensification of land use particularly due to lack of more land to extend agricultural activities. According to Pender (2006), availability of capital, the age of the farmer, education level, and the composition and size of the household are important factors that shape the decisions of the land use intensification by the household. Availability of capital either from farming products or other off-farm activities by the farmer have been known to influence the nature and farming practices (Garrity et. al., 2012). For instance, well-endowed farmers are able to purchase farm inputs like fertilizers, improved seeds and labour to increase food production. The age of the farmer has also been found to influence decisions on farming strategies of households (Polson & Spencer, 1991; Hettig et. al., 2016). The education level enables the farmer to participate in off-farm activities that are likely to provide extra resources to the farming activities that also increases the production (Khatiwada et. al., 2017). The size and composition of the household plays a major role in the choice of farming practices. For instance, a family composed of male members have been known to provide more labour for the household therefore reducing the expenses of hiring extra labour.

In the Nyangores River Catchment, land use/cover have changed considerably as the population increased (Chapter 3). However, the nature of land use intensification has not been adequately studied. This knowledge is important because although land use intensification improves food production it is also detrimental to the environment particularly in terms of soils and the water balance (Hati et. al., 2007). Moreover, Van Eerd et. al. (2014) recommends that proper understanding of the effects of agricultural practices on sustainable cropping systems could minimize soil degradation and thus improve the hydrology of the catchment.

4.3 Methodology

The methods used to collect data included questionnaires, interviews, focused group discussions and observations. The main sampling method was purposive. These data were used to examine the extent of land use intensification that is likely to influence hydrological processes in the catchment. A land use intensity index was computed and used to categorise the farming systems such as shifting cultivation, semi-permanent and permanent systems. This information is important in understanding the proportion of the land under continuous cultivation which could have an impact on soil properties and hence influence the water balance of the catchment.

4.3.1 Sampling frame and sampling methods

The sampling frame was taken as the smallest administrative unit used for population census in Kenya known as a *location* (described in Chapter 3). There are fifteen (15) *locations* in the catchment where households were selected. A local leader (elder) in charge of the social welfare of several households from each location was identified. A household in this case was taken to refer to a group of persons who reside in the same homestead (GOK, 2010). A household was assumed to be the lowest level that influences the land use intensification strategies. The head of the household was any person responsible for the entire household chores including farm activities. A discussion with 15 elders (one from each location) was held to deliberate on the choice of the households that met the criteria to be interviewed. The criteria were set based on the households with farms that had been cultivated and grazed for at least 36 years; the longest time the farmers have stayed in this catchment during the study period (between 1979 and 2015). The sampling method of both the farmers and elders was purposive as proposed by Palinkas et. al. (2015).

Data

Data were obtained through a household survey conducted between October 2015 to June 2016. From the 15 locations in the catchment, ten (10) households from each *location* (identified by the elders) were interviewed. A total of 150 households were selected out of 23107 households in the 15 locations in the whole catchment. The size of a location averages between 10 and 30 km^2 but locations within towns and those fully occupied by forest were excluded since there are no farms. For each household selected, a questionnaire was issued to the head of the household. The questions were based on; i) land use intensity and periods of fallowing; the farmers responded to questions regarding the number of years for cropping before the land is put under fallow during the last 36 years. ii) Land tilling methods; use of hand tilling, ox-drawn tilling, mechanization (tractor) and the no-till. iii) The farmers also responded to questions regarding their socio-economic characteristics including; (a) the age of the head of household, level of formal education (household head was considered to be educated if he/she completed secondary education while farmers considered not educated were those who had primary education and below), household size, and the proportion of male to female in the household and; (b) farm characteristics; these included the size of the farm of the household, fertilizer use, farming experience, types of crops grown and cropping methods (such as crop rotation, mono cropping and intercropping).

4.3.2 Data analysis

Data from the questionnaires and interviews were first processed and coded where necessary.
The following indices were then computed.

Land use intensity index:

The Ruthenbergs' index (R-value) was used to determine the land use intensity as shown in Equation (4.1).

$$R = \frac{\mathrm{C}}{\mathrm{C+F}} \mathrm{X}\, 100 \qquad (4.1)$$

where *R*= land use intensity, *C*=length of cropping period in years, *F*= length of fallow period in a year.

R lies between 0 to100; where, if *R* is less than 33, this kind of farming is designated as shifting cultivation (Ruthenberg, 1971). Shifting cultivation is the agricultural systems that involve an alternation between cropping for a few years on selected and cleared plots and followed by a lengthy period when the soil is rested. When *R* value exceeds 33 but less than 66, it signifies that a semi-permanent cultivation is taking place, and if *R* exceeds 66, then permanent cultivation is said to be happening (Joosten, 1962 as cited in Ruthenberg, 1971).

Socio-economic factors influencing land use intensity

The influence of the socio-economic characteristics on land use intensity and on the tilling methods was done using a multiple linear regression. The land use intensity was the dependent variable while each of the socio-economic characteristics were the independent variables. For each dependent variable, a regression model was applied as in Equation (4.2). The choice of this method was to enable one to see the influence of each of the independent variables on the dependent variable. This model lead to a more accurate and precise understanding of the association of each individual factor with the outcome.

$$y = X\beta + \varepsilon \tag{4.2}$$

where y denotes the dependent variable (land use intensity or the tilling method), X are the independent variables which include household characteristics, and farm characteristics, β are the estimated parameters and ε is the error term.

Factors influencing land use intensity

A combination of descriptive statistics such as the mean, standard deviations and the analysis of variance (ANOVA) were used. ANOVA was used in determining the influence of the socio-economic status on land use intensity and on the use of different tilling methods. The use of ANOVA was chosen since the data had groups that needed to be compared for statistical significance as suggested by Mishra et. al., (2019). ANOVA uses F-statistic shown in Equation (4.3) (Urdan, 2016).

$$F = \frac{\sum n_j(\bar{X}_j - \bar{X})^2/(k-1)}{\sum\sum(X - \bar{X}_j)^2/(N-k)} \tag{4.3}$$

where n_j = is the size of the sample in the *jth* group (e.g. j=1, 2, 3…... k). $\bar{X}_j$ is the mean of the sample in the *jth* group, and $\bar{X}$ is the overall mean. *k* represents the number of independent groups and N is the total number of observations in the analysis.

Since the land use intensity groups did not have equal number of samples, the post –hoc test was done using Brown-Forsythe test statistic in order to show the land use intensity groups that are different from each other. This was done through the transformed response variable that is constructed to measure the spread in each group in Equations (4.4) and (4.5). Let

$$z_{ij} = \left|y_{ij} - \bar{y}_j\right| \tag{4.4}$$

where $\bar{y}_j$ is the median of group j. The Brown-Forsythe test statistic is the model F-statistic from a one way ANOVA on z_{ij}.

$$F = \frac{(N-p)\sum_{j=1}^{p} nj\left(\tilde{z}_{.j}-\tilde{z}_{..}\right)^2}{p-1\sum_{j=1}^{p}\sum_{i=1}^{nj}\left(z_{ij}-\tilde{z}_{.j}\right)^2} \tag{4.5}$$

where p is the number of groups, nj is the number of observations in group j, and N is the number of observations. Also $\tilde{z}_{.j}$ are the group means of the z_{ij} and $\tilde{z}_{..}$ is the overall mean of the z_{ij}. This F-statistic follows the F-distribution with degrees of freedom $d_1 = p\text{-}1$ and $d_2 = N\text{-}p$ under the null hypothesis (Good, 2005).

4.4 Results

4.4.1 Land holding and allocation

The mean size of the total land holding per farmer in the study area was at 4.16 ha, out of which the farmers cultivated 3.26 ha (78.4 %) while 0.9 ha was left fallow (21.6 %). Within the cultivated land the farmers allocated on average 2.00 ha for food crop production (61.4%) while 1.26 ha is allocated for cash crops (38.6%) (Table 4.1). A combination of crops is grown in the catchment including maize, beans, potatoes, peas, cabbages, onions and tea (as a cash crop) either singly or mixed. Most farmers also practice mixed farming where the major livestock kept are cattle, sheep goats and poultry. The outcome of these results show that a high proportion of the farms is under cultivation implying that the soil is undergoing continuous disturbance.

Table 4.1: The mean size of land ownership per farmer

Purpose of land	Mean land holding per farmer	Proportion
Total cultivated (ha)	3.26	78.4 (% of the total holding)
Food crop (ha)	2.00	61.4 (% of the total cultivated)
Cash crop (ha)	1.26	38.6 (% of the total cultivated)
Total fallow (ha)	0.9	21.6 (% of the total holding)
Total holding (ha)	4.16	

4.4.2 Land use intensity index

Land use intensity in this study is based on the R-value. Results showed that only 4.3 % of the farms had low land use intensity (R-value of less than 33). In these farms shifting cultivation method is practiced. The other proportional of farmland (95.7%) was either under semi-permanent or permanent method of cultivation (Table 4.2). This implies that most of the cropland in the catchment is being continuously cultivated. This practice is likely to affect the soil properties which would impact negatively on the water balance in the catchment.

Table 4.2: Land use intensity index in different farms in the Nyangores River Catchment

Index of intensification	Proportion of farms (%)
Land use intensity (R-value≤33)	4.3
Land use intensity (33≤ R-value ≤66)	71.6
Land use intensity (R-value ≥66)	24.1

Note: R-value ≥ 33 is (71.6+24.1) % =95.7%

4.4.3 The influence of the farmer's socio-economic characteristics on land use intensity

The results of the multiple regression analysis showed that there was no significant influence of any of the social economic factors on the land use intensity (results not shown). However, through categorization of land use intensity, the results from the Equations (4.3-4.5) showed that farmers in the low and medium land use intensity groups have more years (10 years) of education than farmers in the high intensity (7 years) groups. The differences in the years of education are also illustrated by the significant robust test of *Brown-Forsythe* of 14.00. However, there was no significant difference in the mean age of the farmer, farm size, house hold size and the population density among the three land use intensity groups ($p \geq 0.05$). The results also indicated that, famers in the high land use intensity group have a significantly higher fertilizer use intensity (239 kg/ha) than those in the medium (161 kg/ha) and in low land use intensity (120 kg/ha) groups as indicated by a significant robust test of *Brown-Forsythe* of 17.53 (Table 4.3). Farmers with higher education were significantly associated with low and medium land use intensity implying that these farmers are likely to engage more in off-farm activities and may therefore have alternative means of livelihood.

Table 4.3: Mean of the socio-economic characteristics of farmers by land use intensity group

Characteristics	Land use intensity group			F. Stat	Robust test
	Low	Medium	High		Brown-Forsythe
Age (years)	34 (5.12)	42 (1.51)	41 (2.34)	0.88	
Farming experience (years)	17 (2.82)	17 (2.61)	20 (2.81)	3.18	
Years of education	10 (1.44)	10 (0.42)	7 (0.46)	10.2*	14.00*
Farm size (ha)	2.8 (0.31)	3.9 (0.29)	5.0 (0.79)	1.88	
Household size (persons)	7 (1.49)	7 (0.26)	8 (0.61)	0.37	
Fertilizer use intensity (kg/ha)	120 (14.5)	161 (9.1)	239 (12.8)	11.89*	17.53*
Population density (persons/km^2)	240 (12.4)	302 (13.5)	287 (10.8)	0.76	

Note: ha = Hectare, *significant at P < 0.05, values in brackets are standard errors.

Classification of farmers on the basis of cropping methods in different land use intensity groups showed that about half the of the farmers (50%) in the low land use intensity group adopted crop rotation while the rest practiced either mono cropping or intercropping. Likewise, in the medium land use intensity group, majority of farmers adopted mono cropping (53.47%) while in the high land use intensity group most of the farmers adopted crop rotation (44.44%) (Table 4.4). Given that majority of the farms (95.7%, see Table 4.2) are in the medium and high land use intensity groups, these results suggest that, mono cropping and crop rotation are the favourable cropping methods in the catchment.

Table 4.4: Percentage of farmers using different cropping methods in different land use intensity groups

Land use intensity	**Cropping methods adopted by farmers (%)**		
	Crop rotation	Mono cropping	Intercropping
Low	50	16.67	33.33
Medium	35.64	53.47	10.89
High	44.44	30.56	25.00

4.4.4 Tilling methods

The common methods of tilling in this catchment were the use of tractor, oxen, hand, and no till. Majority of the farmers use hand tilling (45.7%) while very few farmers use tractors (2.1%). Some of the farmers use a combination of all methods (Table 4.5).

Table 4.5: Methods of tilling the land in the catchment

Method of tillage of land	*Farmers using the method in (%)*
Tractor	2.1
Oxen	42.9
Hand	45.7
No till	6.4
All	2.9

Even though majority of the farmers use hand and ox-drawn tillage methods to prepare their farms, the farmer's socio-economic characteristics showed no significant difference in the means of their age, farming experience, years of education, household size and population density among the tilling methods. However, through the use of robust test of Brown-Forsythe, the results indicate that farmers using ox-drawn tilling had significantly larger farm sizes (5.08 ha) than farmers using hand tilling (3.20 ha) (Table 4.6). But there was no significant difference between the farm sizes of farmers employing hand tillage and those using no till, and between ox-drawn tillage and no till. Similarly, the Brown-Forsythe robust test showed that farmers using ox-drawn tilling had significantly more fertilizer usage (211 kg/ha) than those using the hand tilling (145 kg/ha).

Table 4.6: Influence of the socio-economic characteristics of farmers on tilling method

Characteristics	Ox-drawn till n = 60	Hand till n = 64	No till n = 13	F. Stat	Brown-Forsythe
Age (years)	42.1 (1.77)	41.22 (1.85)	46.54 (4.18)	0.74	
Farming experience (years)	19.9 (0.69)	20.55 (5.75)	21.23 (6.64)	0.38	
Years of education	2.0 (0.11)	3.0 (0.12)	3.0 (0.13)	0.69	
Farm size (ha)	**5.08 (0.44)***	**3.20 (0.38)***	3.78 (0.88)	**5.31***	**5.37***
Household size (persons)	7 (0.38)	6 (0.34)	7 (1.07)	0.82	
Fertilizer intensity (kg/ha)	**211 (16.7)***	**145 (10.38)***	190.39 (23.9)	**6.09***	**6.09***
Population density (persons/km^2)	309.6 (17.8)	133.7 (16.7)	247 (23.5)	1.33	

Note: ha = Hectare *significant at P < 0.05, values in brackets are standard errors.

Comparing the crops that are grown by farmers who employ different tilling methods, results showed that farmers who grow maize/beans used the ox-drawn tilling (67.2%), majority of farmers who grow maize/beans and also grew tea used mainly hand tillage (46. 6%) others use no-tilling (spraying) (36.8%) particularly those growing tea because tea is commonly sprayed to remove weed (Table 4.7).

Table 4.7: Comparing types of crops and tilling methods

Types of crops	Farmers using Ox-drawn tilling (%)	Farmers using Hand tilling (%)	Farmers using No-till spraying (%)
Maize/beans	67.23	9.69	23.08
Tea/maize/beans	16.67	46.56	36.77
Tea/maize/beans/Potatoes	16.10	43.75	40.15

4.5 Discussion

The land use factors that are important to hydrological processes in a catchment that practices mainly subsistence farming include the frequency of use of land (land use intensity) and land tilling methods. These methods were considered in this chapter in combination with other farmers' socio-economic characteristics. This study found that the subsistence farmers' average total land holding is 4.16 ha per household which is higher than the average land holding per household in Kenya which is 1.2 ha according to Syagga & Kimuyu, (2016). Out of the total household land, a relatively large proportion (61.4 %) is devoted to food crop cultivation. This proportion of land size devoted to food crops is similar to that reported by Saka (2011) for farmers (61%) in South-western Nigeria.

Based on the R-value, the main farming practice in this catchment is a combination of semi- and permanent cultivation comprising of 95.7% of the farms (only in 4.3 % of the farms the farmers adopted shifting cultivation). The continuous cultivation is an indication of the need by farmers to grow more food to feed the increasing population (and increased households), as well as cash crop for extra earning as available croplands diminishes. Binswanger-Mkhize and Savastano (2017) in a study of six African countries (Malawi, Uganda, Tanzania, Niger, Nigeria and Ethiopia) also found that in each of the six countries permanent cultivation is practiced and attributed it to high population and reduced fallow periods.

Most of socio-economic factors of farmers could not be quantitatively associated with the choice of the farming practice. However, less years of education and high fertilizer usage were the major factors that enabled the farmers in the high land use intensity group to work out their farms continuously. The education of a farmer has been cited as a factor to low land use intensity since education enables the farmer to engage in off-farm activities that reduces land use intensity (Khatiwada et. al., 2017). Moreover, Oyekale and Adepoju (2012) in South-western Nigeria reported that land use intensity increases when fertilizer usage is high.

The socio-economic factors such as the farm size and fertilizer use intensity were found to be key factors in the choice of tilling methods. The usage of ox-drawn tillage in this catchment signifies an advanced stage in land use intensification (Pingali et. al., 1987; McIntire et. al., 1992; Obsu, 2012). Farm size is a major factor in deciding the tilling method; for instance, Okike (2001) in Nigeria observed that farmers with small farms opted for hand tilling in farm preparation. The results of this study is in line with those of Obsu (2012) in Ethiopia who found that farmers with larger farms used ox-drawn tillage while those with smaller farm sizes opted for hand tilling. The use of ox-drawn tillage could be associated more with farmers growing maize and beans who had larger farms. The use of ox-drawn tillage enabled the farmers to cultivate larger areas hence the use of more fertilizers. The use of hand tilling was also common with farmers with smaller farms under mixed crops (tea, maize, beans and potatoes). The use of hand tilling could be attributed to not only the farm sizes but also to the frequent weeding for the crops particularly potatoes. The no till was common with tea growing areas and was attributed to the frequent spraying of land occupied by tea to eradicate weeds.

4.6 Summary

The aim of this Chapter was to investigate the nature of land use intensification and its driving factors within the sub-humid Nyangores River Catchment. This study found that the average land holding is higher than that of the farmers in the country. More than 95% of the farms were under semi-permanent and permanent cultivation implying high land use intensity. The high land use intensity was attributed to the high population and increased number of households over the last four decades. The increase in the number of households have over the years put pressure on the land given that government policies do not allow expansion of farmlands into the forest (Chapter 3). Intensification of the land use is therefore a means to grow more food and cash crops.

The croplands in the catchment are under subsistence farming where maize, beans, potatoes and tea are cropped using mono-cropping, crop rotation and intercropping. Most of the farmers use ox-drawn tillage, hand and no-till methods farm preparation with only a small percentage using tractors and other farm machineries. Technological input such as fertilizer and animal traction (ox-drawn) for farm preparation are regarded as significant stages in land use intensification. Therefore, this study has demonstrated that land use intensification exists in Nyangores River Catchment that is characterised mainly by continuous cultivation (high land use intensity) and ox-drawn tillage. The intensification of land use established in this chapter has the potential of altering soil properties that may impact on the hydrological processes of a catchment. The influence of land use/cover changes (including land use intensification) on hydrological processes are investigated in the next chapters (Chapters 5,6&7).

CHAPTER 5: THE EFFECTS OF LAND USE/COVER CHANGE ON EVAPOTRANSPIRATION

5.1 Introduction

The aim of this chapter was to examine if changes in land use/cover including the intensified use of land has affected evapotranspiration (ET) in the Nyangores River Catchment. The chapter is part of the third objective of the study which deals with the effects of land use/cover changes on hydrological responses of the catchment. The influence of land use/cover on soil water and runoff are addressed in the subsequent chapter (6). In this chapter, it was hypothesized that reduced forest cover and the subsequent increase in agricultural land have affected spatial variations of evapotranspiration in the catchment. The variability of ET has implications on the hydrology of a catchment.

5.1.1 Factors influencing evapotranspiration (ET)

Evapotranspiration (ET) is an essential element of the hydrologic cycle. ET links the hydrological, energy and carbon cycles (Jung et. al., 2010; Amin et. al., 2020; Tadese et. al., 2020) and returns 60-65% of all the precipitation over land to the atmosphere (Yamazaki et. al., 2011). ET is therefore a significant factor in controlling the water balance. Measurement of ET rates is important in understanding the water balance and effects of human activities (Zhao et. al., 2013; Dile et. al., 2020). Quantification of ET is challenging owing to the many controlling factors including plant biophysics, climate, topography and soil properties (Mu et. al., 2007; Liu et. al., 2020; Bhattarai & Wagle, 2021). The challenges of quantifying ET has therefore created a knowledge gap that has led to difficulties in water resources management (Bhattarai & Wagle, 2021). In the Sub-Saharan Africa where changes in land use/cover are rampant, proper estimation of ET is important for water resources management. This has been hampered by lack of proper quantification of water consumption by plants particularly after land cover transformations due to increasing population (Sungu, 2018). The heterogeneity of vegetation in catchments has made it difficult to estimate ET in different land cover types resulting in uncertainties in the estimation of available water resources (Mwangi et. al., 2016; Kiptala, 2020). Although there are studies of ET variability at global, regional and local scales (Jia et. al., 2009; Gibson et. al., 2013; Nadzri & Hashim, 2014; Odongo, 2016; Liu et. al., 2020), the impacts of changes in land use/cover on ET in each catchment are made complex by the differences in seasons and soil water at these scales and hence may not be generalized (Lambin et. al., 2006).

ET rates estimated from the reference evapotranspiration (ET_o) is independent of crop growth parameters and hence cannot be used in understanding the water loss from different land use/cover types in a catchment (Zotarelli et. al., 2010). On the other hand, the actual evapotranspiration (ET_a) reflects the consumption of water by vegetation in different use/cover types (Sett et. al. (2018). There are various methods of estimating ET_a including the use of in-situ observations (ground observation) and remote sensing techniques (Zhao et. al., 2017; Wang et. al., 2020). The ground observation methods such as use of lysimeters, eddy covariance (EC), and Bowen ratio systems (Bhantana and Lazarovitch 2010) demand sophisticated instrumentation and data interpretations. Furthermore, these methods may not provide spatial trends or distribution of ET_a that is important in catchments with heterogeneous vegetation (Liou & Kar, 2014; Bala et. al., 2016).

The introduction of geographic information systems (GIS) and remote sensing (RS) in the modelling of evapotranspiration provides a cost effective means of estimating ET_a that takes care of heterogeneity of vegetation (Abtew & Melesse, 2013; Shoko et. al., 2015; Nsiah et. at., 2021). Several surface energy balance algorithms have been developed for the estimation of ET_a through modelling. These algorithms include the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et. al., 1998; Turk & Alghannam, 2021), Mapping EvapoTranspiration at High Resolution with Internalized Calibration (METRIC) (Tasumi et. al., 2005; Allen et. al., 2007) and Surface Energy Balance System (SEBS) (Su, 2002). Among these energy balance algorithms, SEBS is more commonly used due to its capability to compute the aerodynamic resistance of heat transfer more explicitly instead of using fixed values (Li et. al., 2009). Aerodynamic resistance plays a key role in estimating total ET in that it varies with environmental conditions for different surface types (Sugita & Kishii, 2002).

SEBS is a single-source energy balance model which estimates atmospheric turbulent fluxes and surface evaporative fraction from satellite data. SEBS is designed for agricultural areas, and has gained use in international studies. SEBS has also been used widely for estimating ET_a in Africa (Elhag et. al., 2011; Gibson et. al., 2013; Shoko et. al., 2015). For instance, Odongo (2016) used SEBS to estimate ET_a in a study to quantify the impact of land use/cover changes on the hydrological response of Lake Naivasha catchment in Kenya. However, SEBS has not been widely applied in estimation of evapotranspiration in the sub-humid areas of Kenya dominated by natural vegetation and subsistence farming.

Numerous satellite images have been used with SEBS to estimate ET including MODIS and Landsat. MODIS satellite images are preferred in homogenous areas such as forests or croplands where distinction of vegetation is clear. However, its coarse spatial resolution (1000 m) is not suitable in differentiating evapotranspiration in different land use/cover types dominated by subsistence farming. On the other hand, Landsat satellite images are preferred due to their relatively higher spatial resolution than MODIS for catchments with heterogeneous vegetation. Estimation of ET in catchments with heterogeneous vegetation is important in managing water resources in a catchment (McCabe & Wood, 2006). Apart from the medium resolution, Landsat images are readily available and freely downloadable (Olang et. al., 2011; Gibson et. al., 2013).

The use of remote sensing in this study was motivated by the fact that the Nyangores River Catchment has heterogeneous vegetation mostly dominated by subsistence farming. The ET of such a catchment would be best estimated using remote sensing and GIS. Some studies estimating ET in the equatorial East African sub-humid region were done at coarse spatial resolutions mainly using hydrological simulations (Githui et. al., 2009; Mango et. al., 2011) while others used surface energy models with coarse spatial resolution (Odongo, 2016; Alemayehu et. al., 2017; Kiptala, 2020). Such methods may not capture explicitly the spatial variability of ET in a catchment with heterogeneous vegetation. For instance, Mwangi et. al. (2016) estimates the distribution of ET in the Nyangores River Catchment using Penman-Monteith. Due to the empirical nature of Penman-Monteith model the results lacks spatial representation.

5.2 Methodology

5.2.1 Datasets

The ET_a was estimated using Landsat 8 satellite images which were obtained for the period between 2015 and 2016 which coincides with the field work data collection. Since Landsat 8 images have a 16-day temporal resolution and 30 m spatial resolution they were suitable in differentiating vegetation in a variety of land cover types. The selected Landsat 8 satellite images were downloaded from the United States Geological Survey (USGS) website https://earthexplorer.usgs.gov/. The digital elevation model (DEM) at 90 m spatial resolution needed for providing the elevations of the catchment to the satellite was obtained from the Shuttle Radar Topography Mission (SRTM) and was downloaded from http://srtm.csi.cgiar.org website. The 90 m spatial resolution DEM was chosen because it sufficiently allows for quantification of land scape features influencing hydrological processes and is consistent for most regions of the world (Olang, 2009). In order to estimate ET_a, cloud free images were needed. Eight images that had an acceptable percentage (about 10%) of cloud cover were selected. Further, the images that represented the dry (07/07/2015& 03/03/2016) and wet (30/12/2015 & 19/03/2016) days were selected to represent the variability of ET_a during wet and dry periods (Table 5.1a). The meteorological data needed by the SEBS model were sourced from Kenya Meteorological Department for Kericho weather station (Table 5.1b). The same data from the Kericho weather station were used to compute the reference evapotranspiration (ET_o).

Table 5.1: Landsat 8 satellite images with OLI-TIRS sensor in the path and row (P169R060) at 30 m spatial resolution, DEM and ground based meteorological data used in the SEBS model analysis.

(a) Landsat images	**Date acquired**	**Cloud cover (%)**
LC08_L1TP_169060_20150112_20180526_01_T1.tar	2015-01-12	8.5
LC08_L1TP_169060_20150213_20170413_01_T1.tar	2015-02-13	1.6
LC08_L1TP_169060_20150301_20170412_01_T1.tar	2015-03-01	2.9
LC08_L1TP_169060_20150317_20170412_01_T1.tar	2015-03-17	0.4
LC08_L1TP_169060_20150504_20170409_01_T1.tar	2015-05-04	6.7
LC08_L1TP_169060_20150707_20170407_01_T1.tar	2015-07-07	2.5
LC08_L1TP_169060_20150824_20170405_01_T1.tar	2015-08-24	7.8
LC08_L1TP_169060_20151230_20170331_01_T1.tar	2015-12-30	0.3
LC08_L1TP_169060_20160216_20180526_01_T1.tar	2016-02-16	0.02
LC08_L1TP_169060_20160303_20170328_01_T1.tar	2016-03-03	10.0
LC08_L1TP_169060_20160319_20170328_01_T1.tar	2016-03-19	4.7
DEM	**Date acquired**	
DEM	2015-01-30	
(b) Meteorological daily data	**length of data**	**Completeness (%)**
Daily minimum and maximum temperatures	2015-2016	100
Relative humidity	2015-2016	100
Wind speed	2015-2016	100
Solar radiation	2015-2016	100
Air pressure	2015-2016	100
Sunshine hours	2015-2016	100

Note: OLI-TIRS-Operational Land Imager and Thermal Infrared Sensor

5.2.2 Data analysis

Pre-processing of Landsat 8 satellite images for SEBS

The first step in the pre-processing is to rectify the images to the Universal Transverse Mercator (UTM) zone 36S in (ArcGIS 10.2.2) and sub-set them to fit in the area of study. Then the processing of the images to provide the input data (images) needed for estimating the ET_a is done; these input data include the land surface temperature, albedo, emissivity, leaf area index (LAI), normalized difference vegetation index (NDVI) and fractional vegetation cover (FVC). Landsat 8 has 11 bands of which bands 1-9 are reflective bands while bands 10 and 11 are thermal infrared bands. The reflective bands were used for estimating albedo, emissivity, LAI, FVC, and NDVI, while bands 10 and 11 were used for estimating the land surface temperature (LST) (see Figure 5.1 for the bands used). The digital numbers for the reflective bands were converted to reflectance while the digital numbers for bands 10 and 11 were converted to radiance following the procedure outlined by USGS, (2013) as cited in Shoko et. al. (2014). The procedure used for the pre-processing of Landsat 8 satellite images is shown in Figure 5.1. The pre-processing of Landsat satellite images, that were to be used as input images (albedo, LST, LAI, FVC, NDVI and emissivity) for SEBS was done in ArcGIS 10.2.2 (for desktop © 1999-2014 ESRI Inc.) since the Integrated Land and Water Information System (ILWIS) (3.7.2) plug-in for SEBS lacks the provision for the processing of Landsat images.

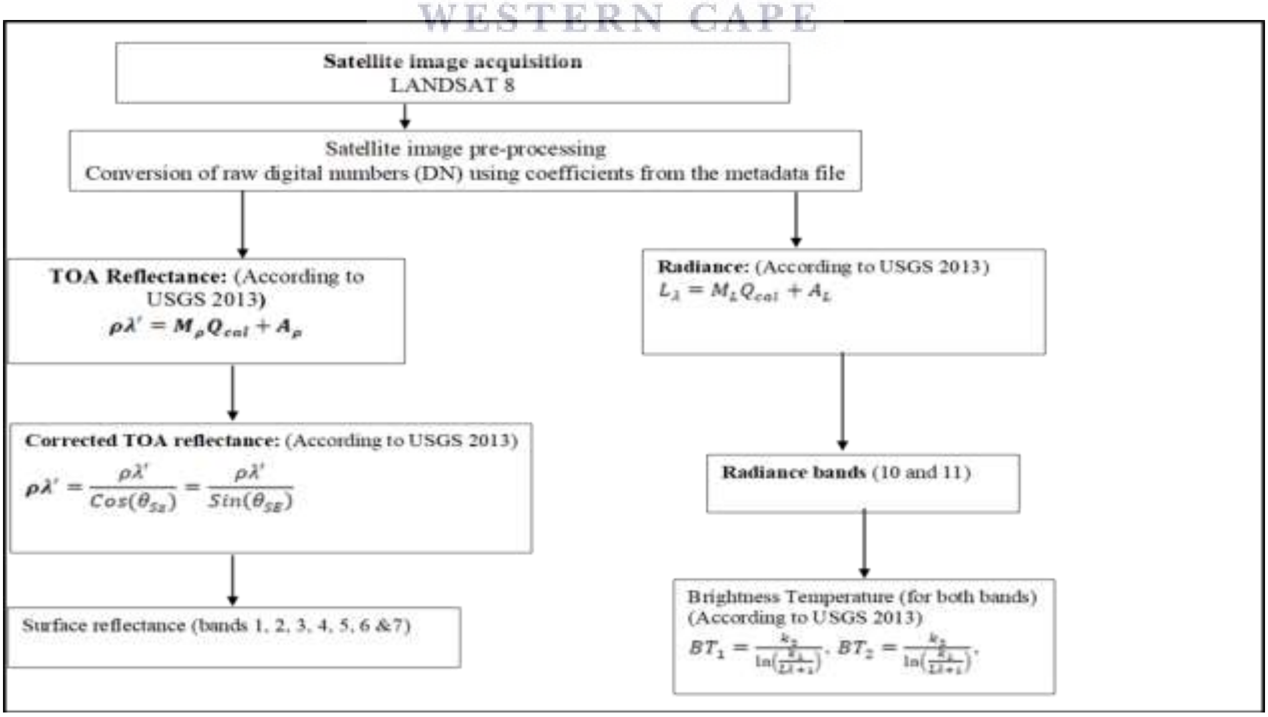

Figure 5.1: Pre-processing of Landsat 8 satellite images

Estimation of ET_a from remote sensing with SEBS

The ET_a was computed by SEBS model using Landsat 8 satellite images. The current set up for SEBS require sets of data including: (1) from remote sensing; albedo, emissivity, temperature and Normalized Difference Vegetation Index (NDVI) to derive surface roughness parameters; (2) meteorological parameters at a reference site (air pressure, temperature, relative humidity, wind speed and sunshine hours) and; (3) radiation data (downward solar radiation, downward long wave radiation). The model consists of three modules: a) to derive energy balance terms; b) to derive stability parameters and; c) to derive roughness length for heat transfer. SEBS was accessed through ILWIS (3.7.2). The open source software package of ILWIS is available at http://www.52north.org. The data required by SEBS for estimating ET_a are summarised in Figure 5.2.

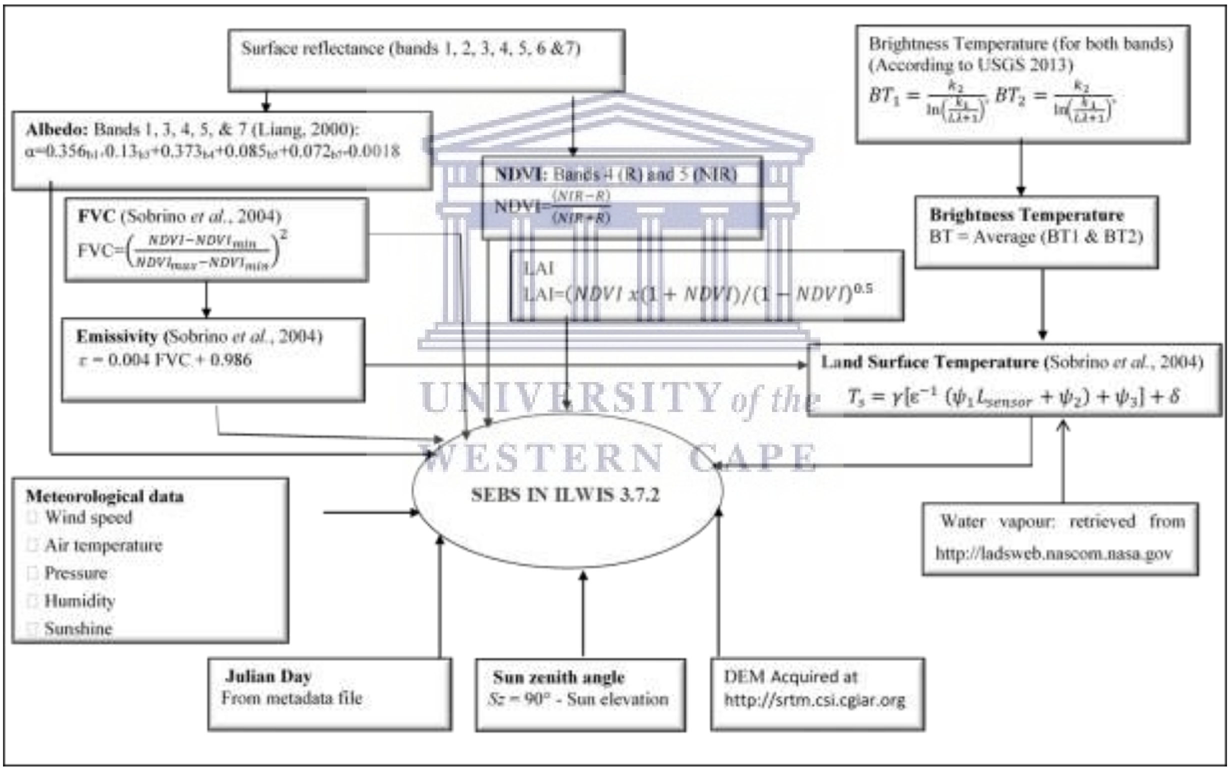

Figure 5.2: Computation of evapotranspiration in SEBS using Landsat 8 satellite images

SEBS estimates daily ET_a from remotely sensed satellite images and meteorological data as inputs by calculating the energy required for water to change phase from liquid to gas as follows:

$$R_n = G_o + H + \lambda E \quad (5.1)$$

where R_n is the net radiation; G_o is the soil surface heat flux; H is the turbulent sensible heat flux, λE is the turbulent latent heat flux and λ is the latent heat of vaporization. In Equation (5.1) the energy for photosynthesis activity and other heat storage terms are considered relatively small and are therefore neglected.

The net radiation flux is the difference between downwards and upwards radiation fluxes at the land surface both in shortwave and long wave spectral domains, and is calculated as:

$$R_n = (1 - \alpha).\, R_{swd} + \varepsilon.R_{lwd} - \varepsilon.\sigma.T_o^4 \qquad (5.2)$$

where α is the albedo, R_{swd} is the downward solar radiation, R_{lwd} is the downward long wave radiation flux, ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant, and T_o is the surface temperature (Su, 2002).

The equation for parameterization of soil heat flux is written as:

$$G_o = R_n.[\Gamma_c + (1 - f_c).(\Gamma_s - \Gamma_c)] \qquad (5.3)$$

where the assumption is that the ratio of soil heat flux to net radiation $\Gamma_{c=}$ 0.05 for full vegetation canopy (Monteith, 1973) and Γ_s =0.315 for bare soil (Kustas & Daughtry, 1990). Interpolation is then done between these limiting cases by applying the fractional canopy coverage f_c.

Equation (5.4) and (5.5) are for calculating the sensible heat flux at the wet and dry limits respectively which differ from the Equations (5.6), (5.7) and (5.8) that are used when the wet and dry limits are reached (Su, 2002).

$$H_{wet} = \left((R_n - G_o) - \frac{\rho C_p}{\gamma_{ew}}.\frac{e_s - e}{\gamma}\right) \Big/ \left(1 + \frac{\Delta}{\gamma}\right) \qquad (5.4)$$

where Δ is the rate of change of saturation vapour pressure with temperature, e and e_s are actual and saturation vapour pressure respectively; γ is the psychrometric constant, γ_{ew} is the external resistance at the wet limit. C_p is the specific heat capacity of air at constant pressure, ρ is the density of air.

$$H_{dry=R_n-G_o} \tag{5.5}$$

$$u = \frac{u_*}{k}\left[ln\left(\frac{z-d_o}{z_{om}}\right) - \Psi_m\left(\frac{z-d_o}{L}\right) + \Psi_m\left(\frac{z_{om}}{L}\right)\right] \tag{5.6}$$

$$\Theta_o - \theta_a = \frac{H}{ku_*.\rho C_p}\left[ln\left(\frac{z-d_o}{z_{oh}}\right) - \Psi_h\left(\frac{z-d_o}{L}\right) + \Psi_h\left(\frac{z_{oh}}{L}\right)\right] \tag{5.7}$$

where *u* is the mean wind speed, *z* is the height above the surface, $u_* = \left(\frac{\tau_o}{\rho}\right)^{½}$ is the friction velocity, τ_o is the surface shear stress, ρ is the density of air, k = 0.4 is Von Karman's constant, d_o is the zero plane displacement height, z_{om} is the roughness height for momentum transfer, Θ_o is potential temperature at the surface, θ_a is the potential air temperature at height z, z_{oh} is the scalar height for heat transfer, Ψ_m *and* Ψ_h are the stability correction functions for momentum and sensible heat transfer respectively, L is the *Obukhov length* defined as

$$L = -\frac{\rho C_p u_*^3 \theta_v}{kgH} \tag{5.8}$$

where g is the acceleration due to gravity, θ_v is the potential virtual temperature near the surface.
If the calculated *H* from Equations (5.6), (5.7), and (5.8) exceeds H_{dry} obtained through Equation (5.5), the dry limit will be assumed to have been reached and Equation (5.5) will be used to calculate *H*. If H_{wet} obtained through Equation (5.4) exceeds *H* obtained from Equation (5.6), (5.7) and (5.8), then the wet limit will have been obtained and Equation (5.4) is used to calculate *H*.

In determining *H*, parameters such as the aerodynamic and thermal roughness are needed. The aerodynamic roughness has a temporal and spatial variation because of; 1) surface roughness and atmospheric stability variations. Surface roughness is the dominant cause of variations in space. The atmospheric stability is the dominant cause of variations in time (Tol et. al., 2009). According to Su (2002) canopy turbulence model should be used to estimate d_o and Z_{om} (Massman, 1997) when the height of vegetation *ho*, leaf area index and wind speed are known. When the height of vegetation is the only one available, Brutsaert (1982) relationship is used:

$$h_o = \frac{z_{om}}{0.136} \tag{5.9}$$

$$d_o = \frac{2}{3} h_o \tag{5.10}$$

The turbulent values of aerodynamic parameters are obtained from land use map if it is available. Equation (5.8) is recommended because aerodynamic parameters depend on surface characteristics as well as wind speed and direction (Su, 2002). Also, the aerodynamic parameters can be related to vegetation inputs of remote sensing where the normalized difference vegetation index (NDVI) is applied (Su & Jacobs, 2001as cited in Gibson et. al., 2013).

$$z_{om} = 0.005 + 0.5 \left(\frac{NDVI}{NDVI_{max}} \right)^{2.5} \tag{5.11}$$

$$z_{oh} = \frac{z_{om}}{exp(kB^{-1})} \tag{5.12}$$

where B^{-1} is the inverse Stanton number, a dimensionless coefficient of heat transfer. In areas that are vegetated, an extended model is used to determine the kB^{-1} value;

$$kB^{-1} = \frac{kC_d}{4C_t \frac{u_*}{u(h)} \left(1 - e^{-n_{ec/2}}\right)} f_c^2 + 2 f_c f_s \frac{k.{}^{u_*}/_{u(h)} . {}^{z_{om}}/_{h}}{C_t^*} + kB_s^{-1} f_s^2 \tag{5.13}$$

where f_c is the fractional canopy cover, f_s is its compliment, C_t coefficient of heat transfer of the leaf and bounded by $0.005N \leq C_t \leq 0.075N$ where N is the number of sides of the leaf to participate in heat exchange. C_t^* is the heat transfer of the soil and is written as:

$$C_t^* = Pr^{-\frac{2}{3}} Re_*^{-½} \tag{5.14}$$

where *Pr* is the *Prandtl* number and the roughness *Reynolds* number Re_* written as:

$$Re_* = \frac{h_s u_*}{\nu}, \tag{5.15}$$

with h_s the roughness height of the soil. The kinetic viscosity of the air is v written as:

$$v = 1.327.10^{-5} \left({}^{p_o}/_{p} \right) \left({}^{T}/_{T_o} \right)^{1.81} \tag{5.16}$$

where p and T are the ambient pressure and temperature respectively, p_o= 101.3 kPa, and

T_o = 273.15 K.

n_{ec} is the wind speed within canopy profile extinction coefficient formulated as a function of the cumulative leaf drag area at the top of the canopy (Massman, 1999b in Su, 2002).

$$n_{ec} = \frac{C_d.LAI}{2u_*^2 / U(h)^2} \quad (5.17)$$

where C_d is the drag coefficient of the foliage elements assumed to take the value of 0.2, *LAI* is the one-sided leaf area index defined for the total area, *uh* is the horizontal wind speed at the top of the canopy.

kB^{-1} required for Equation (5.12) is calculated using Equation (5.13) for vegetated areas while for bare soil the model proposed by Brutsaert (1982) is used;

$$kB_s^{-1} = 2.46(Re_*)^{1/4} - ln[7.4] \quad (5.18)$$

According to formulations by Su (2002), the relative evaporation is derived from the sensible heat flux and the sensible heat flux calculated at the wet and dry limits;

$$\Lambda r = 1 - \frac{H - H_{wet}}{H_{dry} - H_{wet}} \quad (5.19)$$

where Λr is the relative evaporation, H is the sensible heat flux and H_{wet} and H_{dry} are the sensible heat flux at the wet and dry limits respectively. The relative evaporation is in turn used together with R_n, G_o and the latent heat flux at the wet limit to estimate the evaporative fraction.

$$\Lambda = \frac{\lambda E}{R_n - Go} = \frac{\Lambda r.\lambda E_{wet}}{R_n - Go} \quad (5.20)$$

where Λ is the evaporative fraction and λE and λE_{wet} are the latent heat flux and the latent heat flux at the wet limit respectively.

The assumption in SEBS is that the daily value of evaporative fraction is approximately equal to the instantaneous value, since the difference between the instantaneous evaporative fraction at satellite overpass and the evaporative fraction derived from the 24-hour integrated balance is marginal. The instantaneous value is therefore neglected as the evaporative fraction is assumed to remain constant throughout the day (Ahmad et. al., 2005). From this, the daily ET can be calculated as:

$$ET = 8.64 \,.\, 10^7 . \frac{\Lambda \bar{R}_n}{\lambda \rho_w} \tag{5.21}$$

where ET is the daily actual evaporation (mm.d^{-1}), λ is the latent heat of vaporization (J.kg), ρw is the density of water (kg.m^{-3}) and $\bar{R}_n$ is the daily net radiation flux and Λ is the evaporative fraction (Lin et. al., 2008):

$$\bar{R}_n = (1 - C_1).\alpha.k\downarrow_{day} + L_{day} \tag{5.22}$$

where C_1 is the conversion factor taken as 1.1 for instantaneous to broad band albedo, α is broad band albedo that is used in the instantaneous net radiation flux estimation in SEBS, $k\downarrow_{day}$ is the measured or modelled incoming shortwave radiation and L_{day} is daily long wave radiation (Hailegiorgis, 2006). From Equation (5.21) and (5.22) it is clear that, apart from evaporative fraction, albedo is the sole remote sensing variable used in up scaling from instantaneous evaporative to daily ET.

Computation of reference evapotranspiration (ET_o)

Remotely sensed evapotranspiration is associated with uncertainties due to the model structure and the quality of the forcing data (McCabe et.al., 2016). In order to validate evapotranspiration obtained through satellite images, reference evapotranspiration (ET_o) was computed using FAO-56 Penman-Monteith model. ET_o is defined as the rate of evapotranspiration from a hypothetical reference crop closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground (Allen et. al., 1998). ET_o was also used together with ET_a in obtaining the crop coefficients (K_c) values for the most common vegetation in the catchment. The method uses standard climatological records of solar radiation (sun shine), temperature, humidity and wind speed. The choice of this method was guided by the availability of meteorological data representative of this catchment. The model is widely recommended for the estimation of ET_o for validating ET_a from the satellites (Jia et. al., 2009; Turk & Alghannam, 2021) and also for the validation of ET from other models (Maeda et. al., 2011; Ha et. al., 2018). The FAO-56 Penman-Monteith model can be written as:

$$ET_o = \frac{0.408\Delta(Rn - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{5.23}$$

Where ET_o = reference evapotranspiration rate (mm day^{-1}).

Rn = net radiation flux (MJm^{-2}day^{-1}),

G = sensible heat flux into the soil in (MJm^{-2}day^{-1}),

γ = psychrometric constant, (kPa $℃^{-1}$),

T = mean air temperature (℃),

u_2 = wind speed (m/s^{-1}) at 2 m above the ground.

Δ = slope of the saturation vapour pressure curve ($\partial e°/\partial T$) where e°= saturate vapour pressure (kPa) and T = daily mean temperature (℃).

$e_s - e_a$= saturation vapour pressure deficit (kPa) where e_s = saturation vapour pressure and e_a= actual vapour pressure.

Statistical test

The t-statistic was used in comparing the differences in the mean ET_a in different land use/cover types Urdan (2016). The t-test is written as:

$$t = \frac{\overline{ETa}_1 - \overline{ETa}_2}{\sqrt{\left(S^2\left(\frac{1}{n_1}+\frac{1}{n_2}\right)\right)}} \tag{5.24}$$

where $\overline{ETa}_1$ and $\overline{ETa}_2$ are the means of the ET_a from two groups (in this case two different land use/ cover types such as cropland and the forest), S^2 is the pooled standard error of the two groups and n_1 and n_2 are the number of observations in each of the groups.

5.2.3 Land cover map

The Nyangores River Catchment map was provided here to show the land use/cover types and their corresponding areas as used in this study (Figure 5.3).

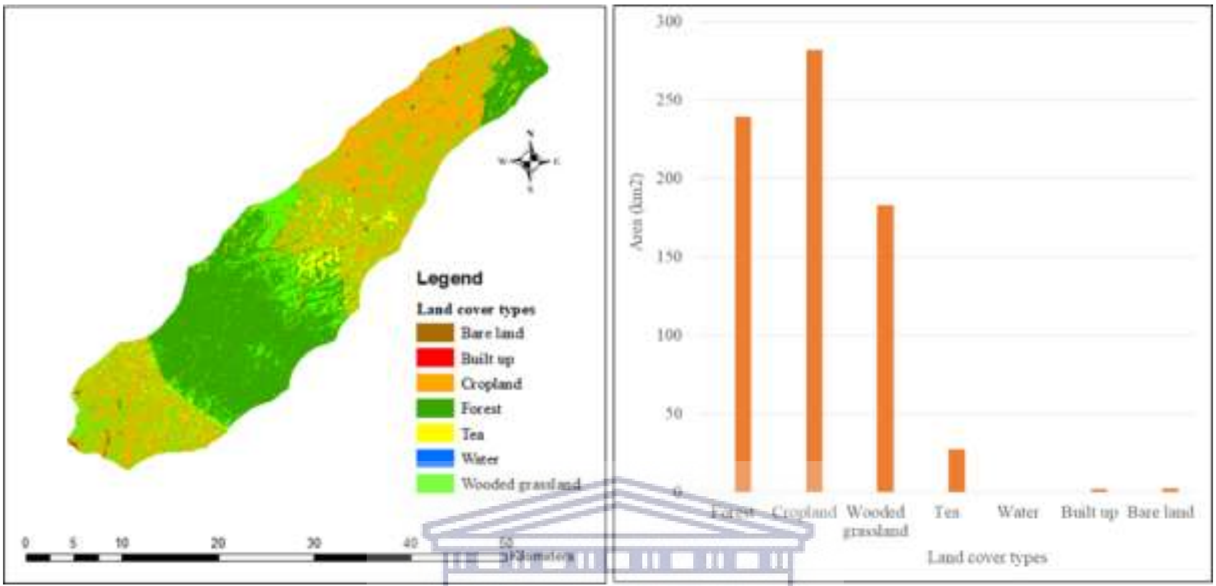

Figure 5.3: (a) Land use/cover types over Nyangores River Catchment (b) Area of land use/cover types. Source-Classified Landsat Satellite image for 2015

5.3 Results

To estimate ET_a for each land cover type from remote sensing, solar radiation components including albedo, LST and NDVI were estimated from Landsat 8. These components were then used as input for SEBS together with other meteorological variables (illustrated in Figure 5.2 above) to compute ET_a according to Equations (5.1-5.22).

5.3.1 Distribution of albedo in different land use/cover types

The surface albedo was highest in the built up and the bare lands with mean values ranging from 0.2 to 0.76 respectively. The high albedo in the built-up and bare lands was attributed to the low absorption, of the incoming radiation associated with buildings and bare lands. On the hand, areas covered with tea, wooded grassland, forest, and water bodies had low albedo values ranging from 0.01 to 0.06 which were attributed to high absorption properties. It was also observed that mean surface albedo was higher during dry periods as compared to the wet periods. For instance, higher values of albedo were observed on 07/07/2015 (0.4) and 03/03/2016 (0.76) which were dry days than on 30/12/2015 (0.3) and 19/03/2016 (0.2) which were wet days (Figure 5.4).

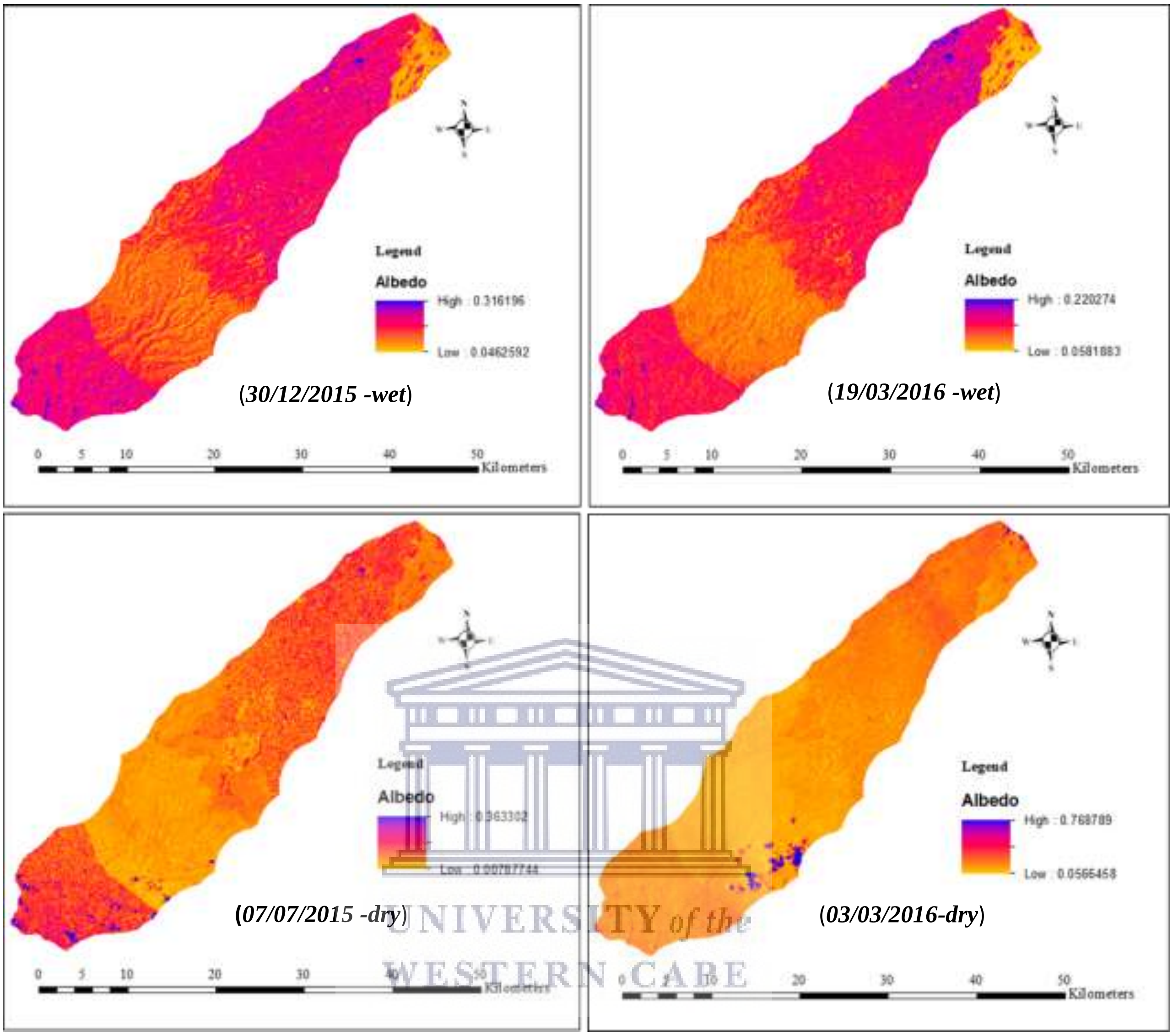

Figure 5.4: Spatial and temporal variations of albedo, over the catchment 2015-2016. Images on 30/12/2015 and 19/03/2016 for wet period, 07/07/2015 and 03/03/2016 for the dry period.

5.3.2 Land surface temperature

The high values of the mean land surface temperature (LST) were found mainly in the built up and bare lands (e.g. 299.45 K on 30/12/2015 and 304.77 K on 03/03/2016) while low values were found in the forest, and in the wooded grasslands (e.g. 273.37 K on 03/03/2016 and 276.77 K on 07/07/2015). Higher temperatures were observed during the dry periods compared to the wet periods (Figure 5.5). Note that built up and bare lands where higher albedo was observed had higher LST. This is attributed mainly to the absence of water to be evaporated and hence most of the heat available is absorbed by the surface materials unlike in the forest where ET is always taking place and using up much of the available heat energy.

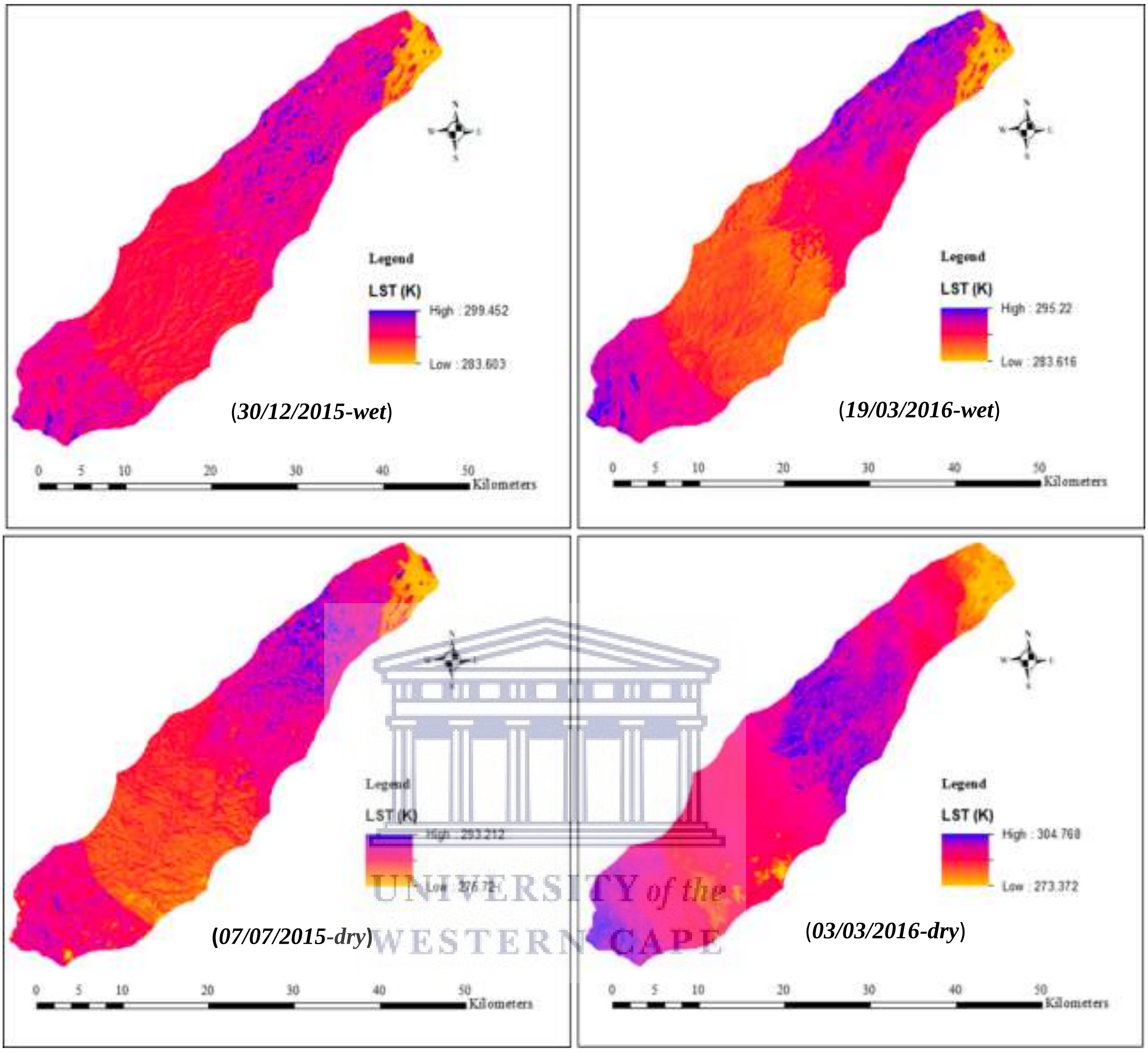

Figure 5.5: Spatial and temporal variations of LST, over the catchment 2015-2016. Images on 30/12/2015 and 19/03/2016 for wet period, 07/07/2015 and 03/03/2016 for the dry period.

5.3.3 NDVI

The NDVI is an indicator of vegetation biomass of the different land use/cover types. High mean values of NDVI were observed in the tea and forest land covers. For instance, the highest mean value of 0.90 and 0.88 were observed on (30/12/2015) and (07/07/2015) respectively. The water bodies had negative values of NDVI with a mean of -0.35 indicative of low biomass (Figure 5.6). The high values of NDVI indicated the high biomass in the tea and forest covers particularly during the wet periods.

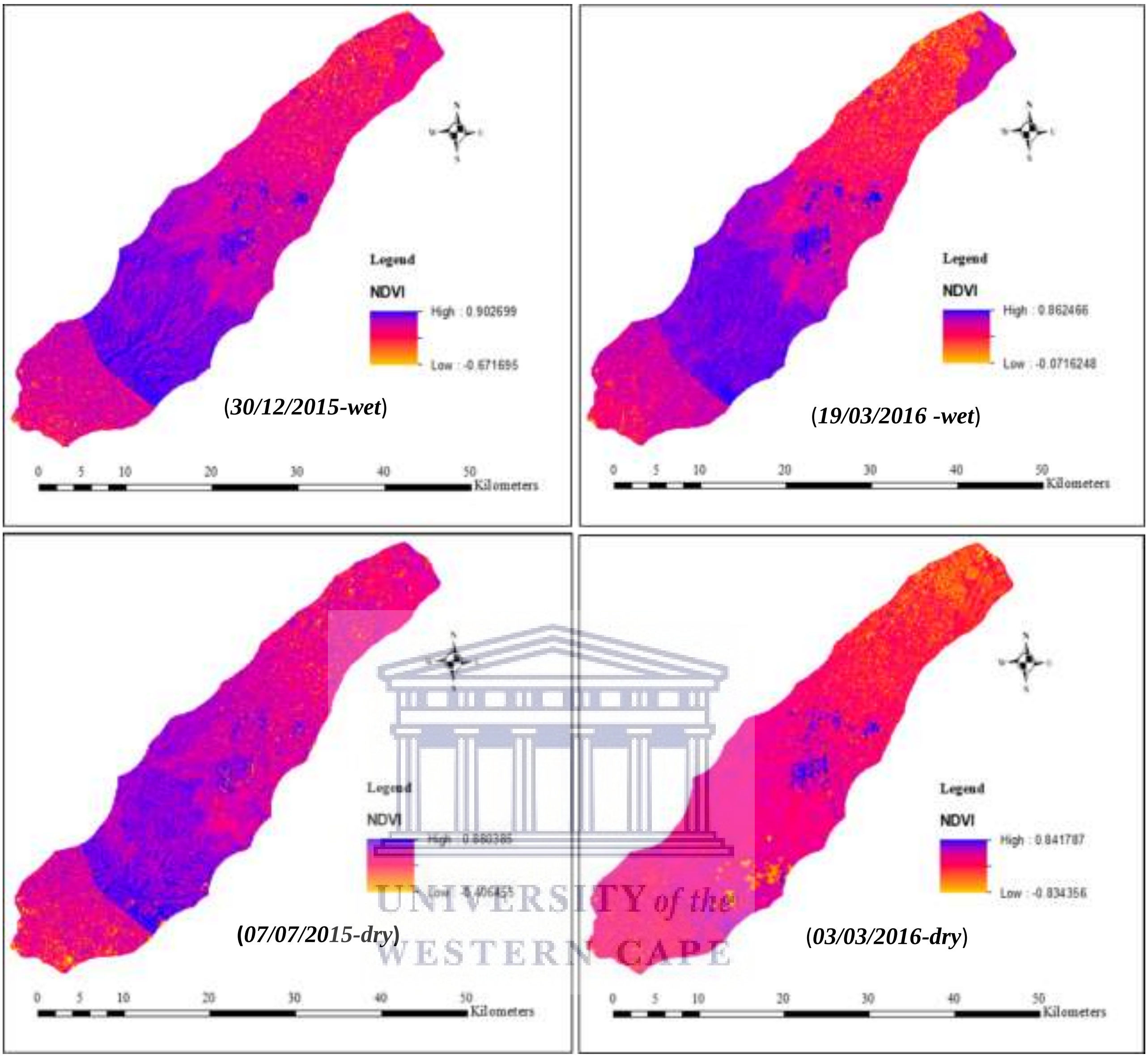

Figure 5.6: Spatial and temporal variations of NDVI over the catchment 2015-2016. Wet days (30/12/2015, and 19/03/2016), b) Dry days (07/07/2015, 03/03/2016)

5.3.4 Net Radiation (Rn)

The net radiation (Rn) was computed according to Equations (5.1)- (5.22). Rn being the actual radiant energy available on the surface, varied across the different land cover types. The forest had higher values than the rest of the land use/cover types (ranging from 357W/m^2 to 432W/m^2). The highest values were registered on the 19/03/2016 and 03/03/2016 images respectively while the lowest net radiation values ranged from 160W/m^2 to 214W/m^2 were registered on 07/07/2015 and 03/03/2016 respectively. The low values of the net radiation associated with the built up areas were attributed to the low surface absorptivity of the urban surfaces (Figure 5.7). It was also noted that the high Rn values were observed during the wet period associated with times of high soil water in the catchment (e.g. 19/03/2016).

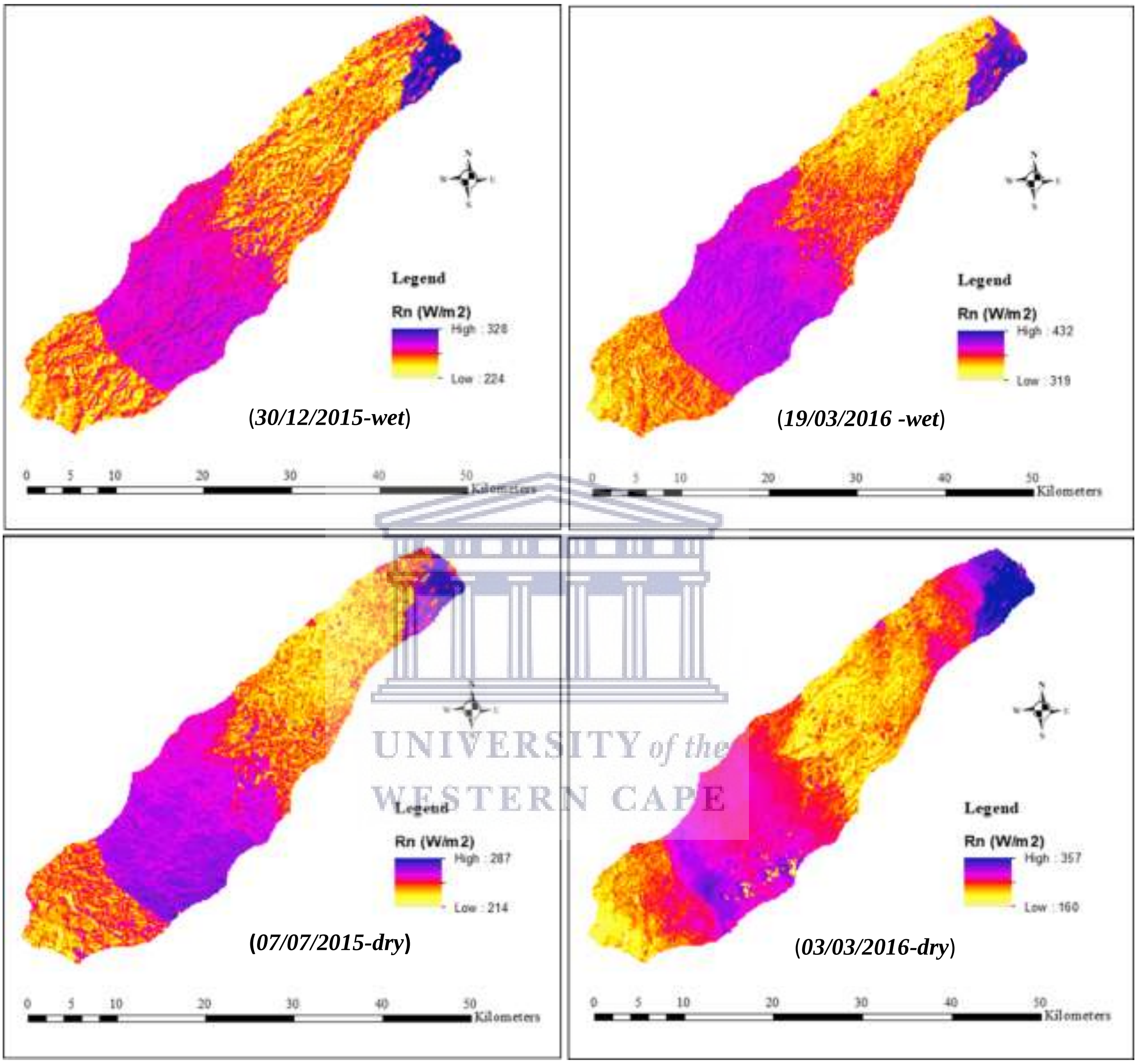

Figure 5.7: Net Radiation a) Wet days (30/12/2015, and 19/03/2016), b) Dry days (07/07/2015, 03/03/2016)

5.3.5 Soil heat flux (Go)

The soil heat flux (Go) which refers to the heat flux absorbed by different soil layers was computed using Equation (5.3). Go also depicted spatial variability in the catchment. The mean value of the soil heat flux was higher in the croplands and bare soils (125W/m^2) than in the forested and wooded grassland areas (24W/m^2) (Figure 5.8). The low soil heat flux in the vegetated areas were due to the interception of radiation by the vegetation. The cropland which are sparsely vegetated and bare lands had higher soil heat flux since less radiation is intercepted thus more energy penetrate into the soil resulting into more soil heat flux.

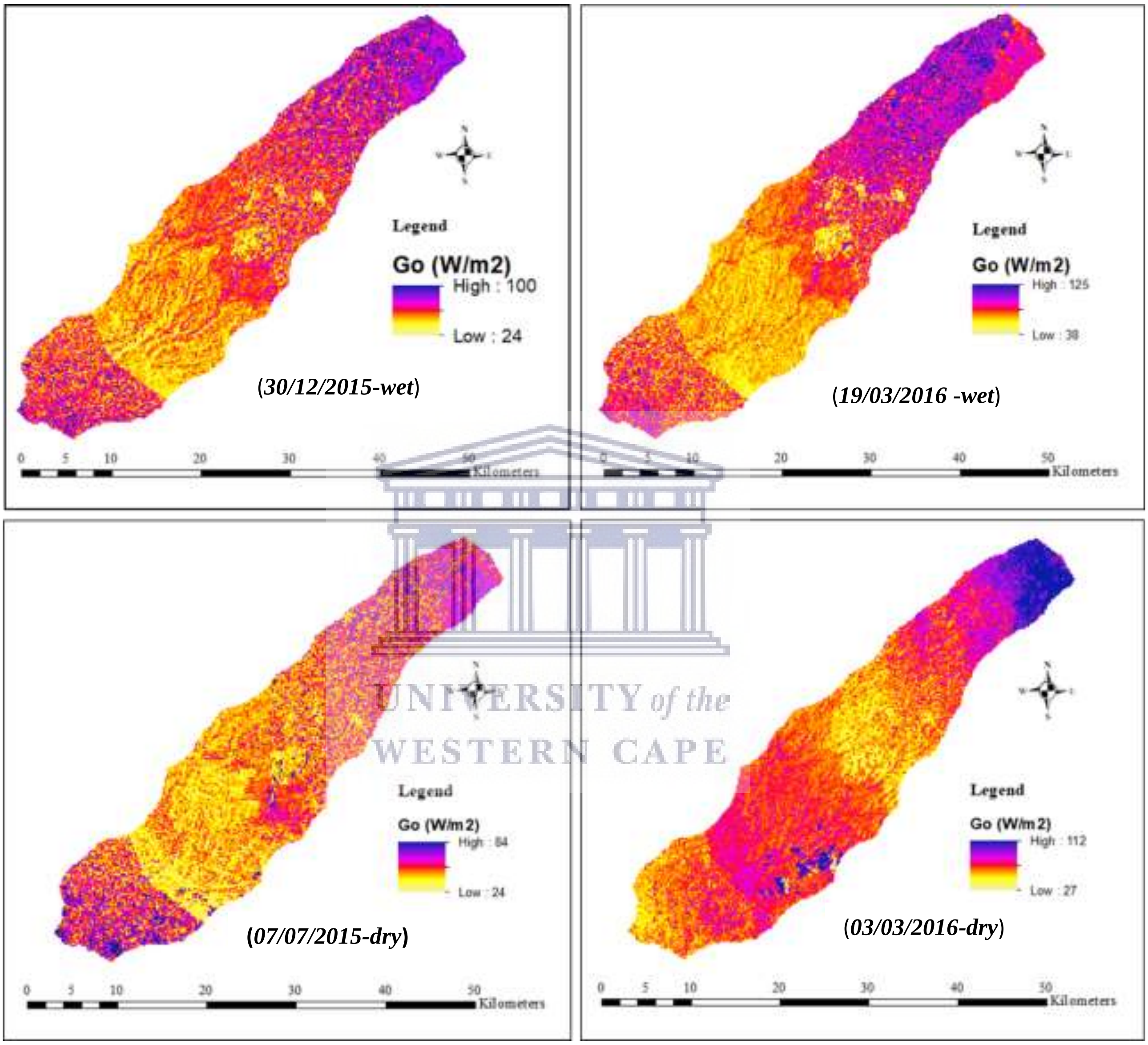

Figure 5.8: **Soil Heat Flux a)Wet days (30/12/2015, and 19/03/2016), b) Dry days (07/07/2015, 03/03/2016)**

5.3.6 Latent heat flux (LE)

Latent heat flux was computed according to Equation (5.19 and 5.20). The highest values of LE were observed in the vegetated areas with values ranging from 194 W/m^2 to 600 W/m^2 while the lowest values were observed in croplands and the bare lands with the highest values of only 73 W/m^2 (Figure 5.9). The forested areas had high values attributed to high moisture content over the areas leading to high evaporation that contributes to high latent heat flux. On the other hand, low values of LE observed in the croplands and bare lands were associated with the low moisture content which does not enhance change of phase. The latent heat flux (LE) was higher during the wet period (e.g. 19/03/2016) than the dry period (e.g. 03/03/2016). This is because, the catchment has more water to evaporate during the wet period.

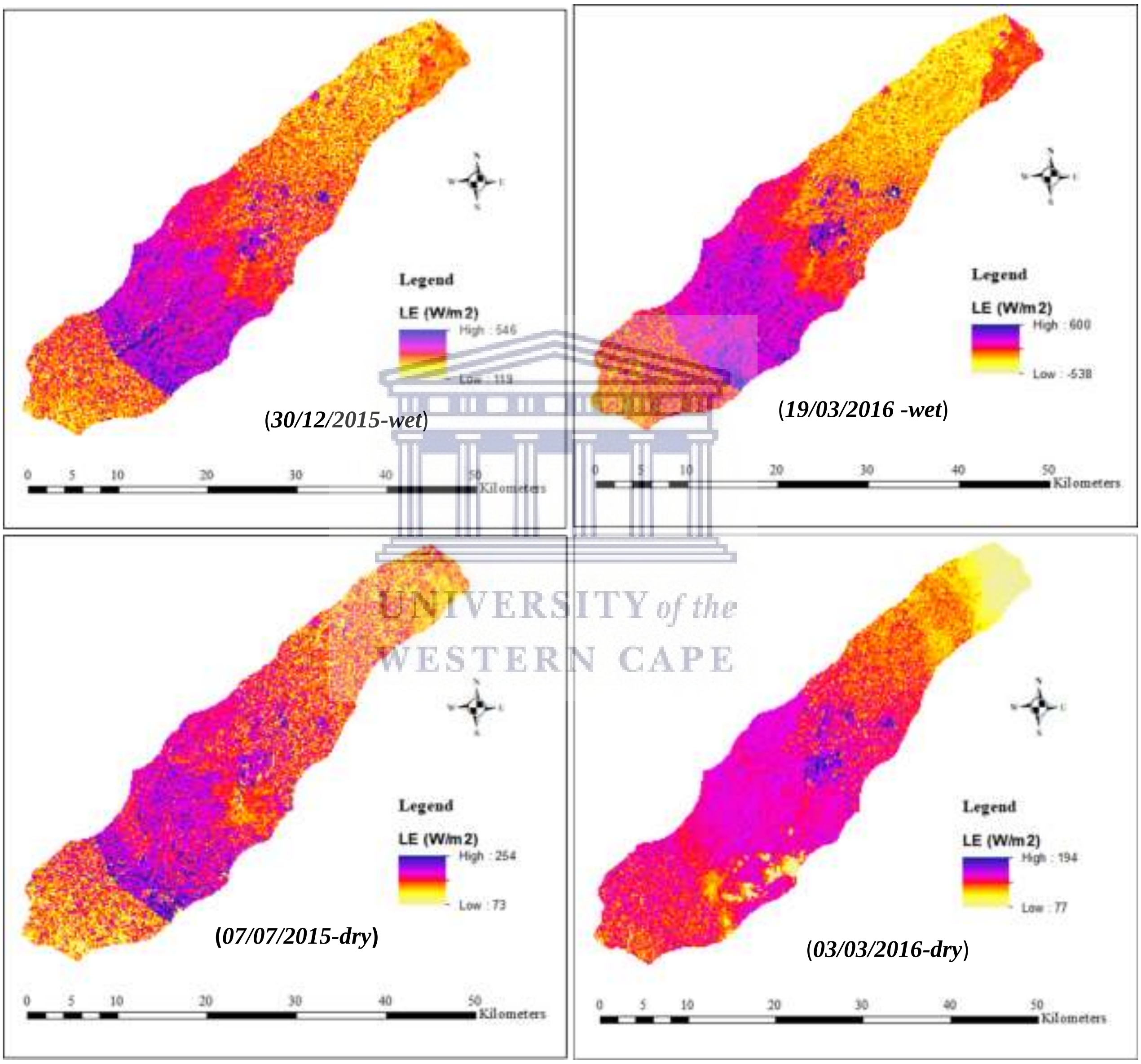

Figure 5.9: Latent Heat Flux a)Wet days (30/12/2015, and 19/03/2016), b) Dry days (07/07/2015, 03/03/2016)

5.3.7 Estimation of actual evapotranspiration (ET_a) using SEBS

ET_a was estimated in SEBS according to Equations 5.21 and using inputs illustrated in Figure 5.2. The results showed that ET_a from the tea and forest areas was higher than ET_a in the other land use/cover types for both wet and dry periods. For instance, on 30/12/2015 and 07/07/2015 (wet and dry days respectively), the forest had mean values ranging from 5-10 mm/day and 4-7 mm/day respectively while bare and built up land had values ranging from 4-5 mm/day and 2-4 mm/day respectively (Figure 5.10). Higher values of ET_a were recorded during the wet periods in all land covers types due to availability of soil water that promotes evapotranspiration.

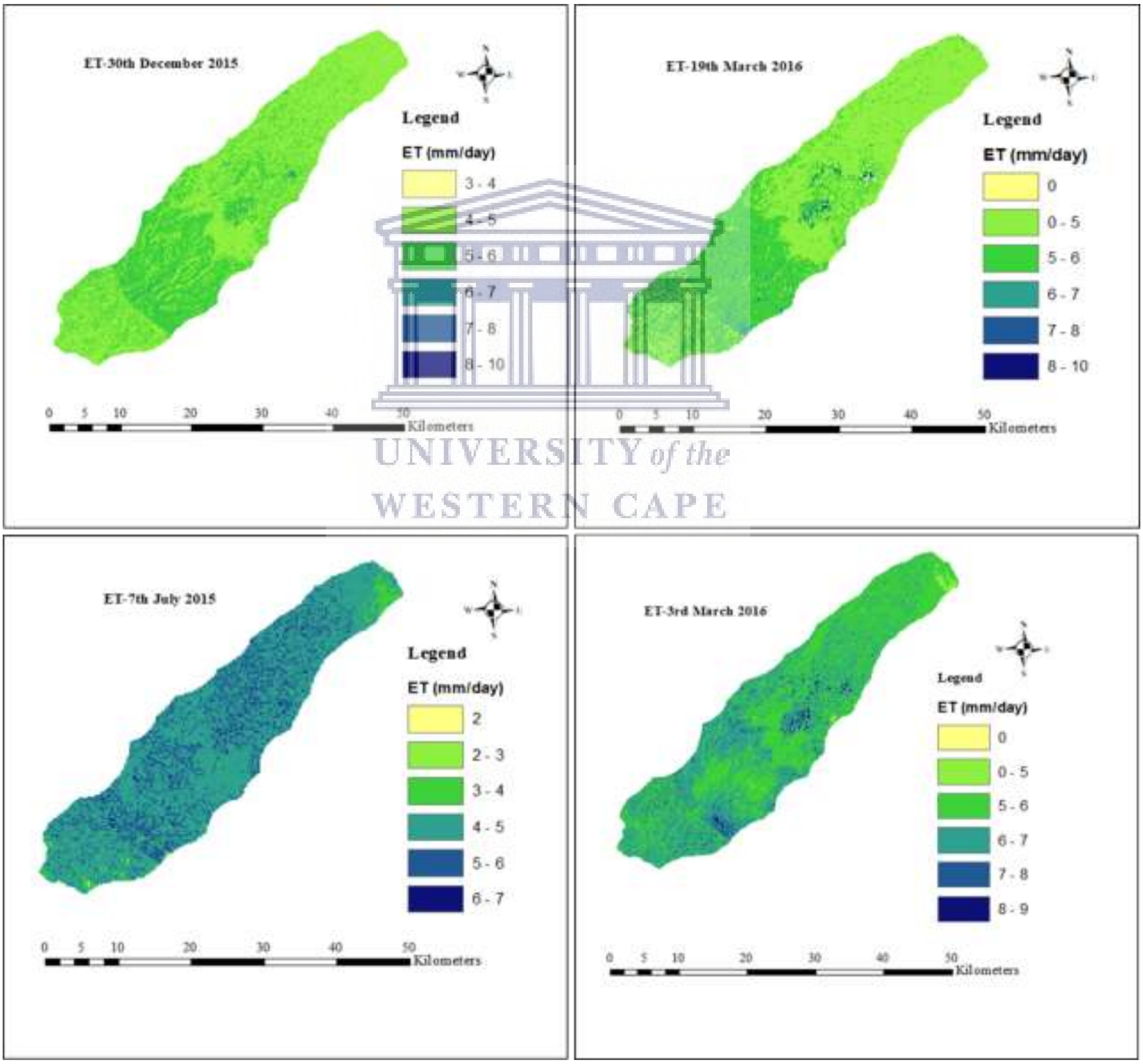

Figure 5.10: Spatial variation of ET_a from Landsat 8 for 30th December 2015 and 19th March 2016 representing the wet period and 7th July 2015 and 3rd March 2016 representing the dry periods.

5.3.8 Validating ET_a using ET_o

The daily ET_o for the period between 20th October 2015 to 20th June 2016 showed that the values ranged between 2-8 mm/day. Higher values were observed between February and March 2016 and between May to June of the same year (Figure 5.11).

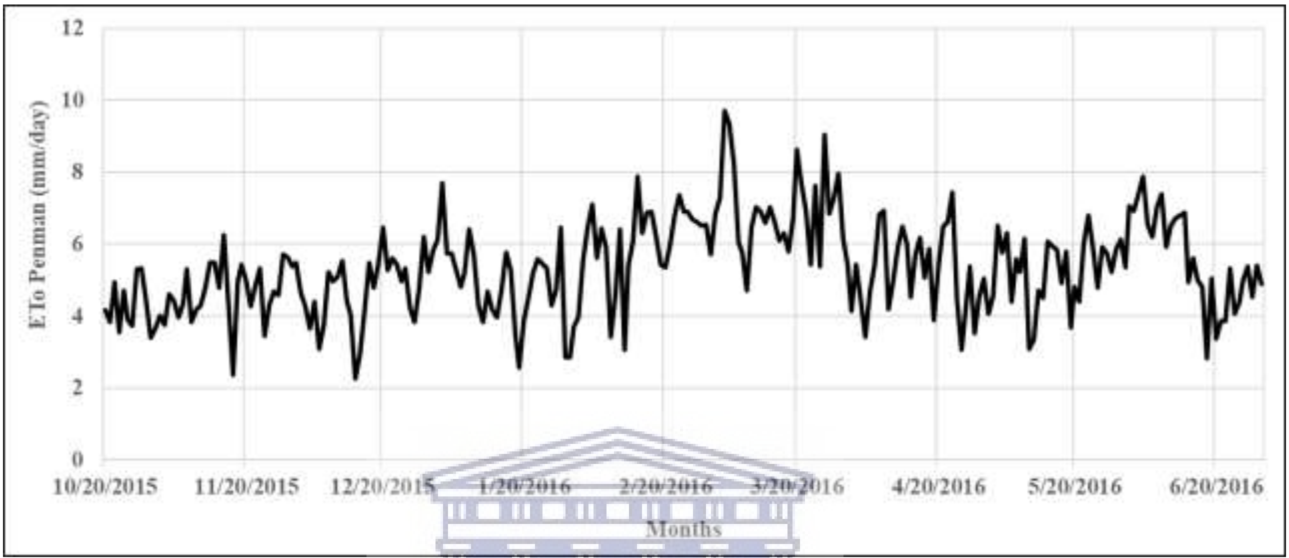

Figure 5.11: Variability of daily reference evapotranspiration (ET_o) for Nyangores River Catchment 2015-2016

The mean daily ET_a values from SEBS model were regressed with those of the daily ET_o from FAO-56 Penman-Monteith. The results showed a correlation of r = ~0.8. The correlation results indicate that SEBS characterized ET_a reasonably well for Nyangores River Catchment (Figure 5.12).

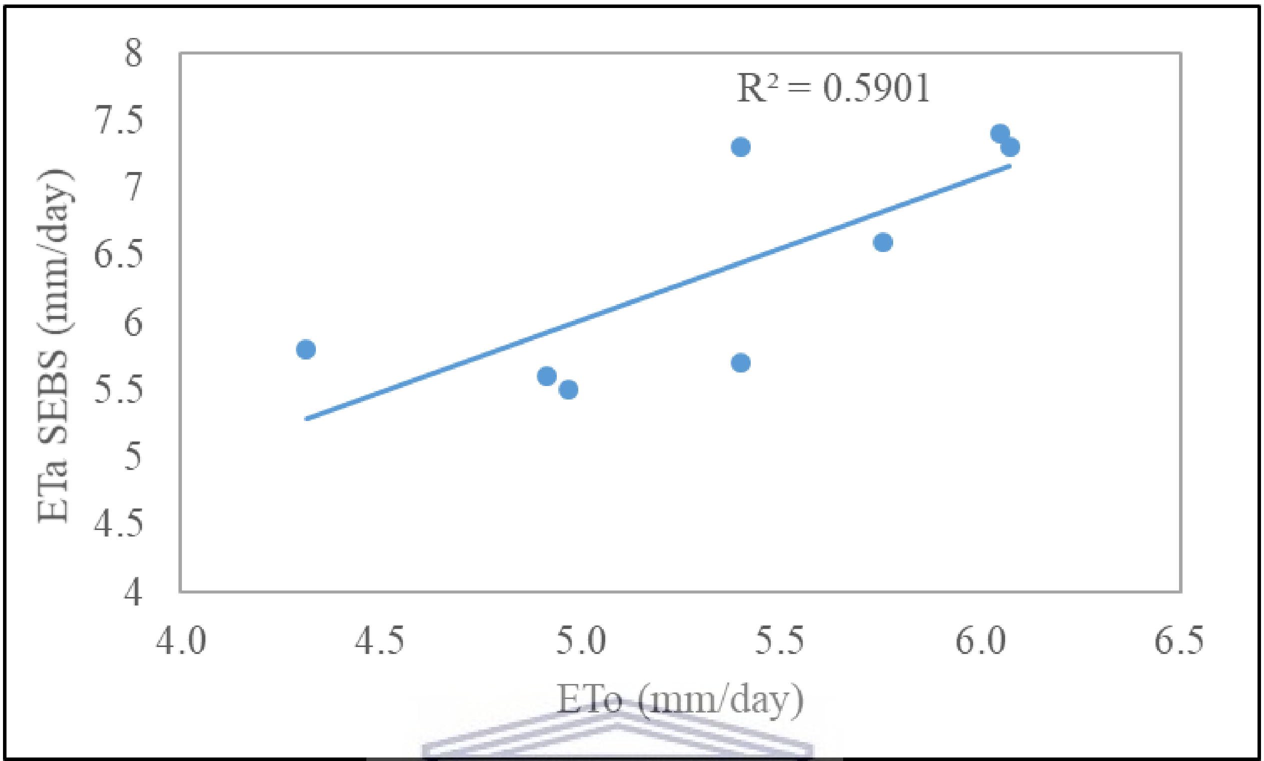

Figure 5.12: Correlation between estimated ET_a by SEBS and computed ET_o by FAO-56 Penman-Monteith

5.3.9 Comparison of ET_a from different land use/cover types

Since the variability of ET_a is not physically quantifiable from the images, values from images were computed and used to examine if the observed differences among land use/covers were statistically significant. This was done by computing mean daily values of ET_a in each land use/cover and comparing them among each other. The results showed that the forest had significantly higher temporal mean ET_a than the cropland, wooded grassland, built up, and bare lands respectively ($p<0.05$). Similarly, the cropland had significantly higher ET_a than the built up areas. However, there were no significant differences in ET_a between forest and either tea or water. Likewise, there were no significant differences between cropland and the wooded grassland, and between cropland the bare land (Table 5.2). These results imply that vegetated areas (mainly forest and tea) have similar ET_a rate with evaporation from the water bodies. The high rate of evapotranspiration in this catchment has the potential to affect water recharge in the river. However, due to the fact that the forest cover has shrunk by over 55 % in favour of mainly the cropland and wooded grasslands (Chapter 3), it is evident that there is less water lost today through ET_a than it was four decades ago when the catchment was mainly forested.

Table 5.2: Comparison of spatial and temporal mean of ET_a from different land use/cover types

LULC compared	Mean (u) ET_a (mm/day)		t-statistic	p-value
FT vs CL	FT_u = 5.98	CL_u = 5.23	5.73*	0.000
FT vs WGS	FT_u = 5.98	WGS_u = 5.16	6.45*	0.000
FT vs T	FT_u = 5.98	T_u = 5.66	1.53	0.171
FT vs BU	FT_u = 5.98	BU_u = 4.54	10.99*	0.000
FT vs B	FT_u = 5.98	B_u = 5.24	3.71*	0.008
FT vs W	FT_u = 5.98	W_u = 5.71	0.904	0.396
CL vs WGS	CL_u = 5.23	WGS_u = 5.16	0.568	0.588
CL vs BU	CL_u = 5.23	BU_u = 4.54	4.43*	0.003
CL vs B	CL_u= 5.23	B_u = 5.24	0.097	0.923

Note: LULC =land use/cover, FT=forest, CL=cropland, WGS=wooded grassland, T=tea, BU=built up, B=bare land, and W=water, * means difference in ET_a is significant at $p<0.05$.

5.3.10 Variation of ET_a /ET_o ratio in different land use/covers

The estimated ET_a from different land use/cover types was compared with the reference evapotranspiration (ET_o) by computing the ratio of ET_a to ET_o. The results showed that the ratio of ET_a to ET_o was more than 0.60 in all the land use/cover types. The relatively high value of this ratio implies that the catchment had ample soil water to support ET in each land use/cover. The ratio of ET_a to ET_o also represent the crop coefficient (K_c) values for the vegetation found in the different land use/cover types in the catchment. On average the forest had the highest K_c value (0.94) followed by tea (0.89). Grass and maize had the lowest K_c values of 0.81 and 0.82 respectively. However, in some days, forest and tea were transpiring beyond the ET_o. For instance, on 30/12/2015 (a wet day) the ET_a for forest and tea was 1.07 and 1.09 respectively. On the other hand, the water body evaporated beyond the ET_o during the dry days (Figure 5.13). These results imply that when the catchment has enough soil water it enhances evapotranspiration more in areas covered by forest and tea.

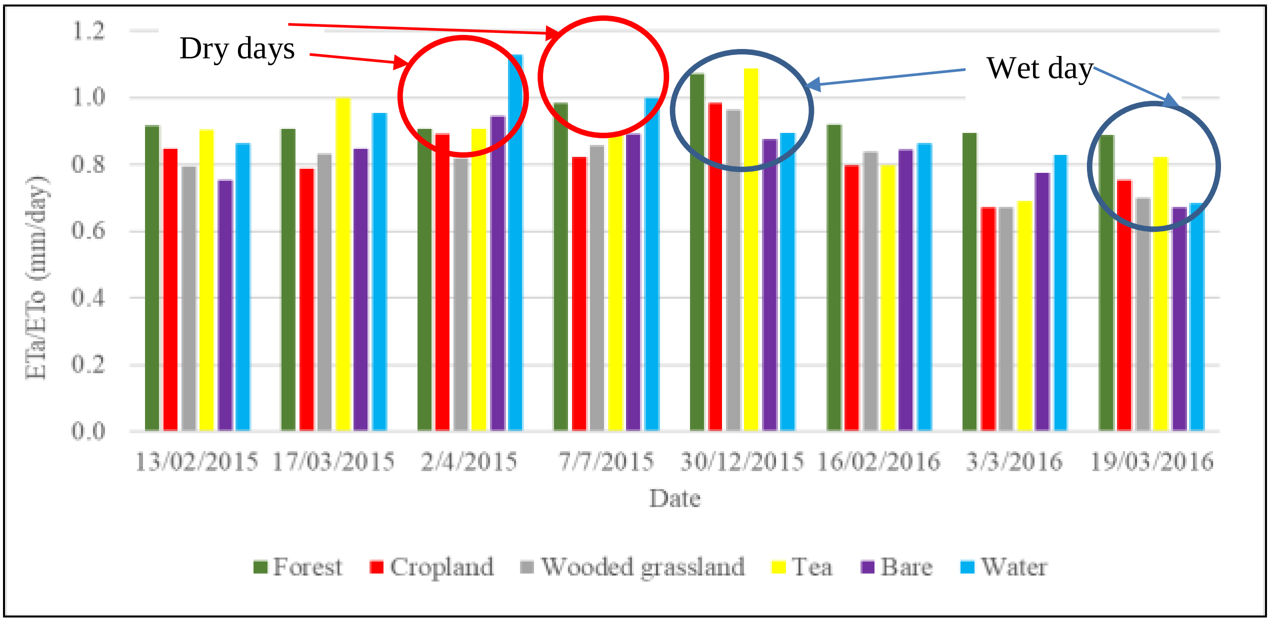

Figure 5.13: Variation of ET_a / ET_o ratio of some selected days in different land use/cover types

5.3.11 Water lost from different land use/cover types through ET_a

The water lost through ET in the catchment was estimated by converting the mean ET rates (mm/day) to volume (m^3/day) for each land use/cover type. Although the forest had the highest mean ET rate, the results showed that the volume of water lost by cropland in 2015 was higher (1507.3 m^3/day) than that of forest (1423.8 m^3/day). The higher volume of water observed in the cropland in relation to other land cover types was due to the large area occupied by this land cover. The tea area has lower volume of water lost despite having a high ET_a rate due to the small area it occupies in the catchment. Note also that, although the built up, bare and water land covers have substantial ET rate, the volume of water lost per day is negligible due to the small areas each occupy. However, in 1979, the highest volume of water was lost by the forest since it had the largest area and highest ET_a rate. Comparing the total water lost per day in the catchment in 1979 (4240.6 m^3/day**)** and in 2015 (4047.8 m^3/day), the results show that the catchment is retaining more water now when the forest cover has reduced by more than 50%. For example, the forest area decreased over time from 531.9 km^2 in 1979 to 239.4 km^2 in 2015 and the amount of water lost through ET_a decreased from 3157.3 m^3 /day in 1979 to 1423.8 m^3 /day; which is more than double (Table 5.3). These results suggest that although the catchment has undergone massive land use/cover changes, the net water lost through ET_a is less than before these changes occurred.

Table 5.3 Comparison of mean water lost (m^3/day) through ET_a from different land use/cover types between 1979 and 2015

	1979	2015	1979	2015
Land cover type	**Area (km^2)**	**(Area km^2)**	**ET_a (m^3/day)**	**ET_a (m^3/day)**
Forest	531.53	239.7	3157.3	1423.8
Cropland	104.34	282.8	556.1	1507.3
Wooded grassland	89.93	182.9	464.0	943.8
Tea	10.3	27.0	58.3	150.0
Built up	0.01	2	0.01	9.1
Bare land	0.66	2.3	3.5	12.2
Water	0.23	0.3	1.3	1.7
Total	**737.0**	**737.0**	**4240.6**	**4047.8**

5.4 Discussion

The actual evapotranspiration (ET_a) of the Nyangores River Catchment was estimated using remote sensing and the SEBS model. The influence of land use/cover changes on the surface energy balance affects the variability of ET_a of a catchment. Therefore, there were spatial and temporal variations of the surface energy balance components depending on the type of land use/cover and the season (wet or dry). For instance, in the forest land where albedo was low, the net radiation was observed to be high. Conversely, in the built up, bare and cropland where albedo was high, the net radiation was low. Similar findings were found by Tursilowati et. al. (2012) in Semarang-Indonesia who observed that built up areas had lower net radiation than the vegetated areas. The land surface temperature was lowest in the forest and water areas due to the consumption of energy in evaporation and transpiration. Although bare and built up land had higher albedo than the forest, it was observed that the LST in the bare and built up areas was higher than in all the other land use/cover types. The high LST in the bare and built up areas was attributed to higher absorption of the available net radiation by the building materials (such as rocks, concrete, etc.) and also to the low water available for evaporation and/or transpiration unlike in the forest and water body. Therefore, the absorbed radiation in bare and built-up land increases the surface temperature more than in the forest where much of the solar energy is used up in evapotranspiration. Abera et. al. (2020) in a study in Voi (Kenya) indicate that although an albedo increase causes an increase in the reflected shortwave radiation which consequently causes a local cooling effect, the reduction of latent heat flux in bare land is comparatively stronger and outweighs the albedo effect, thus leading to net warming; this consequently leads to the increase in LST.

ET_a in a given land use/cover type is mainly a function of the Rn. The Rn in this study was observed to be higher in the forest than in the sparsely vegetated areas such as the croplands, bare and built up areas. The mean ET_a estimated from SEBS Model in each land use/cover compared fairly well with that of the reference ET (ET_o) computed using meteorological variables of a station within the catchment (r~ 0.8). Jia et.al. (2009) used a similar validation method in a catchment in the Yellow River Delta (China) and found similar values (r~0.8) that were reported to be satisfactory. Therefore, the estimated ET_a in the different land use/cover types in the catchment was compared in order to examine how each land use/cover loses water.

The results indicated that the general distribution of ET_a was mainly controlled by the land use/cover type and the weather conditions. Due to availability of water taken from the soil by plant roots, ET_a was higher in the highly vegetated areas (forest and tea bushes) than in the built up and bare lands. A similar observation was made by Sett et. al. (2018) in Northern India who indicated that forest had a higher ET than the agricultural and urban areas. The values of ET_a observed from different land use/cover types in this catchment were comparable to those obtained in similar catchments. For instance, Munishi-Kongo (2013) reported that ET_a rates in the evergreen forests was higher than in cropland in Kilombero River Basin, Tanzania. Likewise, Kongo et. al. (2011) observed that ET_a from indigenous forest and water bodies was higher than in croplands in the Thukela River Basin, South Africa.

The ET_a was also used to characterize the crop coefficients (ratio of ET_a: ET_o) (K_c) of each vegetated land use/cover using the ET_o. The forest and tea bushes had an average K_c value of about 0.9; in which the highest value was beyond 1.0 during the wet periods. Crop coefficient values more than 1.0 implies that the forest is losing water through ET_a beyond the ET_o. The K_c value of the grassland and maize were 0.81 and 0.82 respectively. The K_c values of the forest and grassland agree with those of the standard K_c values for such crops by Allen, et.al. (1998). However, K_c values for maize and tea were higher than the standard ones (0.6-0.35) since maize was mainly intercropped with beans in the catchment. Similarly, the K_c value obtained here for maize (0.82) was within the values that were found by Kiptala (2016) (0.3-1.0) in the Pangani River Basin, Eastern Africa.

Although the ET_a rates were highest in the forest, the volume of water lost (in m^3/day) through ET was highest in the croplands since cropland had a larger total area than the forest. From Chapter 3, the Nyangores River Catchment has lost more than 50% of the forest cover mainly to crop and wooded grassland over the last four decades. The volume of water lost by the forest (1423.8 m^3/day) was more than half of what the forest was losing before it was converted to other land use/cover types. Furthermore, the net water lost in the catchment in 2015 was found to be less than in 1979 when the forest cover was larger than the other land use/covers. Consequently, due to the decrease of the forest cover, the catchment is losing less water since the land use/covers that were created from the forest have significantly lower ET_a rates. The knowledge of the amount of water lost through ET_a in different land use/cover types is vital for water management in a catchment. This is particularly so in catchments that are undergoing extensive land use/cover changes.

5.5 Summary

The aim of this Chapter was to examine if land use/cover changes has affected how water is lost through ET in the catchment by comparing ET_a rates in different land use/cover types. ET_a for the different land use/cover types was estimated using the remote sensing method. The SEBS algorithm was used to characterise ET_a in this catchment using Landsat 8 satellite images and the ET_a was validated using computed reference ET. The validation results showed that remote sensing using SEBS model is adequately applicable in data scarce catchments to estimate ET_a. Particularly, the use of Landsat 8 satellite images at 30 m (pixel) spatial resolution made it possible to adequately estimate ET_a in each land use/cover in the heterogeneous catchment. This study specifically established the spatial variation of ET_a in the catchment through examining the surface energy balance elements including albedo, net radiation, soil heat flux and the latent heat flux. The main observation was that forest and tea areas in this catchment had significantly higher ET_a than the other land use/cover types. The crop factors (K_c) of the most common vegetation types in the catchment were characterized. The values were on average comparable to K_c values of similar catchments. However, the average K_c values of forest and tea were lower than the standard values except during the wet period when the values were equal or slightly more. This is because the vegetation in the study area were under natural weather conditions in a sub-humid equatorial region unlike the standard values that are normally computed under controlled conditions. Considering the amount of water lost through ET in the catchment, cropland had the highest mean volume/day during the study period (although the forest had higher ET_a rate than cropland). This observation was attributed to the fact that the area under cropland is larger than the area under forest cover and rainfall during the study period was higher than the long-term mean; implying that the cropland had vegetation throughout this period. Considering that part of the forest was converted to wooded grassland, bare and built up areas that have significantly lower ET rates than croplands and tea, net water lost through ET in the catchment was less than when the forest was intact. The reduction of the amount of water lost through ET_a implies that there is more soil water available in the catchment. The long-term implications of the altered ET_a together with soil water and surface runoff (investigated in Chapter 6) to the Nyangores River was investigated in Chapter 7.

CHAPTER 6: THE EFFECTS OF LAND USE/COVER CHANGE ON SOIL WATER AND RUNOFF GENERATION

6.1 Introduction

In this chapter the influence of the changes in land use/cover including land use intensification on soil water and runoff generation was examined. This chapter is part of objective 3 which is considering how the land use/cover changes influence the hydrological response (ET, soil water and runoff) in the Nyangores River Catchment. In this Chapter, it was hypothesised that the rampant land use/cover changes before the late 1980s (Chapter 3) and later the increased land use intensification (Chapter 4) has altered the physical properties of soils that consequently affect soil water content and runoff generation in the catchment. A brief review of soil water and runoff generation is discussed in the next sections.

6.1.2 Soil water and surface runoff

Soil water is important in controlling the exchange of heat fluxes between the land surface and the planetary layer (D'Odorico et. al., 2000). Soil water also influences the success of agriculture and, regulates surface runoff and sub-surface water storage (Venkatesh et. al., 2011). Although soil water influences vegetation structures (Porporato et. al., 2002), vegetation on the other hand exerts important controls on the whole water balance through various interactions with the hydrological processes (Chhabra et. al., 2006; Naha et. al., 2020). Land use/cover can affect soil water through changes in plant species (Chen et. al., 2009; Tellen & Yerima, 2018; Assefa et. al., 2020). For instance, Li et. al. (2009) observed that land use change from woodland to grassland reduced soil water by 18% in the loess Plateau in China. The loss of soil water was attributed to the decrease in rainfall interception and transpiration. Land use change can also influence infiltration of water into the soil (Li et. al., 2009; Chemura et. al., 2020). Liu et. al. (2008) observed that infiltration in the forest was greater than that of the farmlands and grasslands in the Loess Plateau, China.

Soil water is mainly influenced by land use through changes in soil properties such as the soil bulk density, soil organic carbon (SOC) and texture (Yimer et. al., 2008; Abrol & Sharma, 2012; Bonini et. al., 2020). The alterations of soil properties may lead to low infiltration and consequently low soil water and high runoff generation (Al-Seekh et. al., 2009; Zhou et. al., 2010; Azarnivand et. al., 2011). Studies have shown that increase of bulk density reduces soil water and increases surface runoff generation due to the reduction of infiltration of water into the soils (Radácsi, 2005; Adekalu et. al., 2006; Manfreda, 2008; Al-Seekh et. al., 2009; Kavian et. al., 2014). On the other hand, increase in soil organic carbon (SOC) increase soil water due to increased porosity leading to high infiltration (Molina et. al., 2007; Kavian et. al., 2014; Panagea et. al., 2021). Changes in land use/cover may change both the plant species as well as the soil properties, and therefore becomes a major factor in soil water variability (Chen et. al., 2010; Gao et. al., 2014; Niu et. al., 2015; Chemura et. al. 2020; Wubie & Assen, 2020). Together with land use/cover, rainfall patterns and the antecedent soil water also influence soil water availability (Gao et. al., 2014). Much of the focus of water balance variability is in the semi-arid catchments where water is a limiting factor in food production (Western et. al., 2003). However, the much needed understanding of the impacts of land use/cover modifications on the water balance in the sub-humid regions is scarce. For instance, the status of soil water variability in the Nyangores River Catchment that has experienced massive land use/cover changes has not been studied. Studies that have assessed the influence of land use/cover changes on hydrological systems in this catchment have not considered the effects of these changes on soil water content (Mango et. al., 2011; Defersha & Malesse, 2012).

Accurate soil water data are essential for water balance estimation. Various methods are used for estimating soil water including monitoring sensors such as; EC-20 (Decago Devices, Inc), Delta T-Devices including ML2x SM 200, and ML3 ThetaProbe (Abbas et. al., 2011). The ThetaProbes, for instance have been used widely in measuring soil water content in different soils and in calibration of other soil water measuring probes (Delin, 2005; Loiskandl et. al., 2010; Abbas et. al., 2011). ThetaProbes measures water content by measuring the dielectric constant which establishes the velocity of an electromagnetic wave through the soil (Muñoz-Carpena et. al., 2004; Delin, 2005). The ML3 ThetaProbe is ideal for measuring soil water content in different land cover types at different depths (Qiu et. al., 2001).

Apart from direct measurement of soil water, hydrological models are normally used especially when soil water is required at daily time steps. Soil water modelling is particularly useful to determine the influence of rainfall on soil water in different land cover types. Many hydrological models use generalized or uniform land cover, soils, and rainfall data that lead to under/over estimation of soil water (Qiu et. al., 2001). Catchments with heterogeneous land covers requires soil water information at fine spatial resolution for use in the understanding of the water balance. Therefore, for accurate estimation of soil water particularly in catchments with heterogeneous land cover, one dimensional models such as the Hydrus-1D are appropriate (González et. al., 2015;

Caiqiong &Jun, 2016; Gabiri et. al., 2018). The Hydrus -1D model simulates soil water vertically through soil layers in different land cover types at daily time intervals therefore improving on the spatial/temporal resolution of the estimation of the soil water content especially in data scarce catchments (Gabiri et. al., 2018). The model has advantages over other models since it can be used in modelling soil water content in catchments with both agricultural and natural land covers (Rubio & Poyatos, 2012; González et. al., 2015; Marković et. al., 2015).

Understanding the runoff process is important in the water balance in a catchment. Runoff in a catchment is the combination of multifaceted hydrological processes which not only rely on the catchment characteristics (such as the vegetation, land use/cover, and soil properties) but also a function of the antecedent conditions and rainfall characteristics (Parsons & Stone 2006; Rodríguez-Blanco et al.et. al., 2012). Many methods have been used for estimating runoff generation in different catchments. Mainly hydrological models such as Soil and Water Assessment Tool (SWAT) are used. However, the hydrologic response unit (HRU) used in SWAT assumes a single-ecological environment in land cover and uniform human activities (Quinn et. al., 2005). This makes them unsuitable for use in catchments with heterogeneous land cover and varied human activities (Narasimhan et. al., 2005; Li et. al., 2010). Empirical method such as Runoff Coefficient (RC) (Geiger et. al., 1987) are recommended for measuring runoff generation in such catchments. This method uses data that is directly collected from the field that can be experimentally validated (Berihun et. al., 2019). Direct measurement of runoff in experimental plots can also be employed to study runoff generation in different land cover types (Taye et. al., 2013).

6.2 Methodology

6.2.1 Description of experimental work

Most studies of runoff and soil water availability have been widely done at catchment scales (Detty & McGuire, 2010; Penna et. al., 2011; Farrick & Branfireun, 2014). Considering that land use/cover changes occur at the farm level and therefore influence rainfall partitioning at this level, runoff and soil water variability were studied experimentally using small (2x3m) plots. The experimental plots were established to monitor runoff generation and soil water content in different land use/cover types in the catchment. The plots were preferred for the estimation of surface runoff, and soil water content since they provide detailed and high quality data that are not influenced by topographical and rainfall variations (Kinnell, 2016). Field measurements of surface runoff, soil water and soil properties were done for 10 months covering the two main rainfall seasons in Kenya. The rationale of using different land use/cover types was particularly to examine the effects of land use intensification through subsistence farming (Chapter 4) on surface runoff and soil water. Hence, the forest and wooded grasslands in this study were considered as having the least human influence from subsistence farming activities, while the croplands (cultivated) and grazed lands represented the disturbed land by human activities. The farms selected for the experiments were representative of the catchment and had similar soil, topography, geology, and climate in order to make comparisons of the influence of human activities on hydrological processes in this catchment viable.

The selected cropland area was occupied by maize (*Zea mays*) and the soils were Mollic Andosals with soil types mainly clay loam in the 0-15 cm depth, clay in the 25-70 cm depth (Figure 6.1a). The grazing land composed of Kikuyu grass (Waithiru, 2009) with rooting depths of 30 cm that was used for grazing cattle. The soils were composed of loam in the 0-5 cm depth, clay loam in the 10-15 cm depth and clay in the 25-70 cm depth (Figure 6.1 b).

Figure 6.1: Photographs showing the nature of human activities in the catchment (a) the maize farm (cropland) (b) the grazing land where runoff and soil water data were taken.

The forest was an indigenous afromontane mixed forest composed of different types of tree species such as *Dombeya guetzenii, Croton macrostachyus, Hagenia abyssinica, and Prunurs africana*. The vegetation in the forest is dominated by broad leaved trees with heights greater than 20 m and forms a closed canopy and undergrowth (Figures 6.2 a, b, c & d). These trees grow in the high altitudes of 1600-2250 m.a.s.l (Kinyanjui et. al., 2013).

Figure 6.2: Photographs showing the undisturbed forest land: (a) and (b) shows the sizes of trees (c) the underneath of the trees and (d) the canopy of trees during the dry season in the Nyangores River Catchment.

The wooded grassland area is composed of short grass with scattered shrubs (Figure 6.3). The soils are Mollic Andosals with soil types mainly sandy loam in the 0-5 cm, loam in the 10-15 cm clay loam in the 25-30 cm and clay in the 45-70 cm depth.

Figure 6.3: Photo showing the undisturbed wooded grassland composed of grass and scattered shrubs.

The experimental plots were located in different parts of the catchment where soil type was the same in order to help in the comparison of the results of surface runoff and soil water from different land cover types (Figure 6.4).

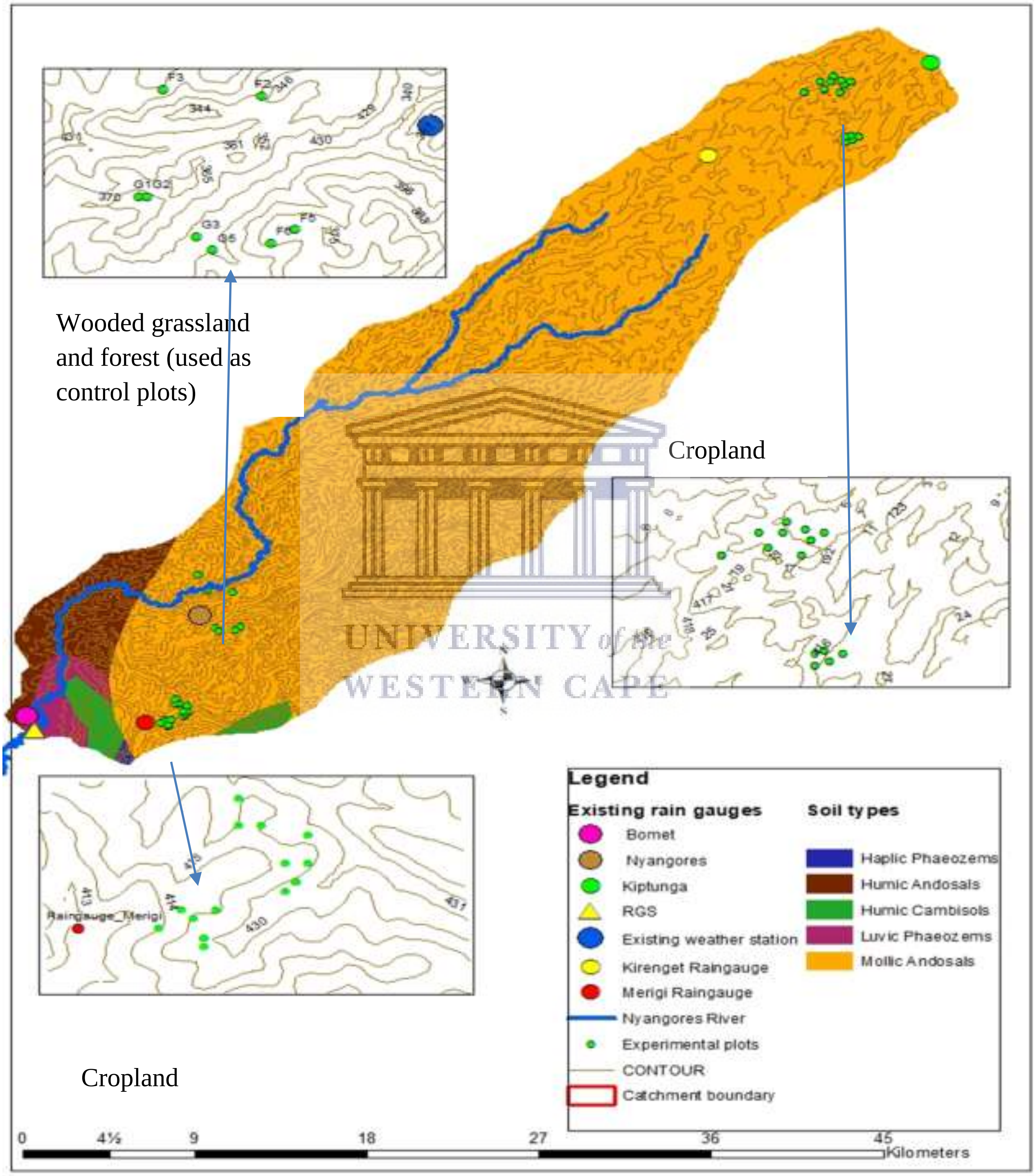

Figure 6.4: Locations of runoff plots and soil moisture measurements in the catchment. Also shown are the existing (Bomet, Nyangores and Kiptunga) and installed raingauges (Merigi and Kirenget), and the regular gauging station (RGS) at Bomet.

6.2.2 Data types

Although much of the work in this chapter was experimental, supplementary secondary rainfall data were provided by Water Resources Management Authority (WRMA) (Kenya) for the period between 1980 and 2009. Temperature and leaf area index (LAI) data that were used in modeling soil water were obtained from the Kenya Meteorological Department (KMD) and USGS (https://lpdaac.usgs.gov) respectively. All the other data types were measured experimentally from the field. These data included daily rainfall, soil water content, surface runoff, soil bulk density, soil organic carbon (SOC), porosity, infiltration, soil texture, and the hydraulic conductivity (K) (Table 6.1).

Table 6.1: The data used to assess soil water and surface runoff from the different land use/cover types in Nyangores River Catchment

Data type	Source	Need for the data
Daily rainfall	Raingauges in the field	Daily rainfall in mm /day, used for establishing the relationship between soil water and rainfall, for establishing the rainfall-runoff relationships and for running the Hydrus-1D model.
	WRMA	Used for comparing with the rainfall collected by the rain gauges.
Daily runoff	Experimental plots	Daily surface runoff was required for comparison of the land use/cover response to rainfall.
Soil physical properties	Field samples (at five depths)	Soil physical properties were required for comparing the changes in soils that have taken place in different land use/cover types and as inputs for calibration of the Hydrus-1D model.
Soil water content (SWC)	Measured in the field (at five depths)	SWC was important for calibrating Hydrus-1D model and simulating for daily soil data to be used in comparing the differences in spatial and temporal soil water availability in various land use/cover types and for assessment of the influence of soil water to runoff generation.
Max, min, mean temperatures, extra-terrestrial radiation, and wind speed.	Kenya Meteorological Department (KMD) for Kericho station ID No: 9035279	Required for estimating the relative humidity and for running the Hydrus-1D model.
Leaf Area Index (LAI) from MODIS satellite images	From Land Processes DAAC (LP DAAC) Website https://lpdaac.usgs.gov	LAI was required for calculating potential soil surface evaporation, potential transpiration for Hydrus-1D model.

6.2.3 Data collection within plots

Ten (10) experimental plots (measuring 3x2 m each) in each land use/cover type were delineated. The land use/cover types included cropland (that was planted with maize), grazed land, wooded grassland and forest (see Chapter 3). In each plot several variables including, soil physical properties, soil water and surface runoff were measured. In each land use/cover type, each variable measured was averaged to get values representative for that land use/cover type.

Measurement of rainfall

Rainfall data were collected using two tipping bucket rain gauges (HOBO Raingauges RG3-M) installed inside the catchment at $0^0$46.917'S, $35^0$24.107'E at an altitude of 2273 m.a.s.l (located at Merigi) and $0^0$28.542'S, $35^0$40.017'E at an altitude of 2624 m.a.s.l (located at Kirenget) (Figure 6.5). The installed rain gauges collected rainfall from October 2015 to June 2016. Rainfall measurements were automatically taken and recorded at 0.2 mm increments.

Figure 6.5: (a) Hobo raingauge for measuring rainfall (b) Downloading data from the raingauge

Soil sampling

The soil samples for each land use/cover type were taken. For the undisturbed land (i.e. forest and wooded grassland), the samples were taken from ten different locations within the catchment. For the farmlands (crop and grazed), 10 farms used for subsistence farming (approximately 2 ha each) were used for the soil sampling; the samples were taken from the cropland and grazed land respectively. The selected farms were those that had been cultivated and/or grazed for at least 36 years. The choice of the 36 years was based on the longest period that the farms have been in use since the start of conversion of the forest to cropland and grazing land. Studies also show that the spatial and temporal changes of soil properties after land use changes are likely to take place after such a time (Abrol & Sharma, 2012; Akintoye et. al., 2012). The sampling sites in the farm were selected 10 m away from the hedges/fences to avoid the hard and compacted surfaces on paths that can influence the measurements.

For each farm, the soil samples were taken at five depths including 0-5 cm, 10-15 cm, 25-30 cm, 40-45 cm and 65-70 cm. The selection of the soil depths was guided by studies that have shown that the temporal and spatial variability of soil properties vary with depth and land use/cover type. For instance, a study by Azlan et. al. (2012) in Malaysia found that silt and clay contents increased with increasing depth from 0-30 cm. Another reason for considering these depths is that maize and grass that were the common crops in this catchment were found to extend up to 70 cm. Therefore, the reason for taking soil samples in the various soil depths was to be able to evaluate the effects of human activities on the soil properties in different land cover types.

The soil samples were taken for the purpose of determining the soil bulk density, SOC, porosity, texture, hydraulic conductivity (K) and also for the calibration of ML3 ThetaProbe that was used for measuring the soil water content in different land use/cover types. Soil bulk density is commonly measured by collecting a known volume of soil using a metal ring pressed into the soil and determining the weights (McKenzie et. al., 2004). The tools used for measuring soil bulk density were: a steel ring measuring 10 cm length x 7 cm diameter, a shovel, an oven proof dish, oven, and weighing balance (measuring in grams). The ground where bulk density was determined was at least 10 m away from the fence. An undisturbed flat horizontal surface was prepared with a spade at the required depth where the soil sample was taken. The steel ring was pushed into the soil gently with a wooden hammer making sure that the soil inside the ring was not compacted. Three rings were pushed into the soil for sampling at each depth. In order to remove the ring from the soil, excavation was done to loosen the soil around the ring and the ring was removed carefully. The excess soil outside the ring was removed. The labels of the various rings that were used for a particular depth of the soil were recorded, then the rings were closed on both sides and packed ready for analysis in the laboratory. Soil samples for texture, organic carbon content, porosity and hydraulic conductivity were collected in the same pit and at the same depths with that of the bulk density and placed in plastic bags that were well labelled (Figure 6.6).

Figure 6.6: Preparing soil samples from the field for the laboratory testing of soil bulk density, SOC, texture, porosity and hydraulic conductivity (K) from October 2015 to June 2016.

Soil infiltration measurements

Infiltration measurements on different land use/cover types were made using a double ring infiltrometer (Bertrannd, 1965). Double ring infiltrometer is a well-known technique for directly measuring soil infiltration rates (Bouwer, 1986; ASTM, 2009; Gregory et. al., 2005). More details on the use of the double ring infiltrometer can be found in Lili et. al. (2008). The infiltrometer used for this study had an outer ring diameter of 60 cm and the inner ring 30 cm. The cylinders were driven 10-12 cm into the soil using a metal plate and a sledge hammer (Figure 6.7). A measured amount of water was added into the cylinders 20 cm above the soil surface. The rings were refilled to 20 cm head each time when the head approached 5 cm above the soil surface. Infiltration was recorded at time increments of 0, 1, 2, 5, 10, 15, 20, 30, 40, and 60 minutes, and continued until no more infiltration was recorded with the help of a hook gage and a steel tape placed over the rings and until constant infiltration was achieved. The measurements were taken in the cropland, grazed, wooded grassland and forest lands in triplicates during the dry period so that the soil was dry.

Figure 6.7: Measuring soil infiltration using double ring infiltrometers in (a) cropland (b) forest and (c) grazed lands in the dry season February 2016.

Soil water measurements

Soil water content was measured in the four land use/cover types at various depths. The data were required for calibrating Hydrus-1D for simulating the daily soil data to be used in comparing the differences in spatial and temporal soil water variability in various land use/cover types. The data were measured using ML3 ThetaProbe. Prior to soil water content measurements, the ML3 ThetaProbe was calibrated using gravimetric water content (oven dry) measurements. Then soil water measurements were made using the calibrated ML3 ThetaProbe at five soil depths 0-5 cm, 10-15 cm, 25-30 cm, 40-45 cm and 65-70 cm in the cropland, grazed land, wooded grassland and in the forest. Soil water measurements were made away from the fence and large trees which would influence the soil moisture content. ML3 ThetaProbe was used together with a hand held HH2 moisture meter suitable for field work (Figure 6.8) (refer ML3 user manual, version ML3-UM-2.1 Jan 2017 downloadable at www.delta-t.co.uk). The choice of ML3 ThetaProbe was based on its accuracy of measuring volumetric soil moisture (±1%), and its portability. ML3 ThetaProbe is also safe to use since unlike the neutron meter method it does not radiate emissions (Sarani and Afrasjab 2012). ThetaProbes have been widely used in research on soil water measurement (Schneider et. al. 2008).

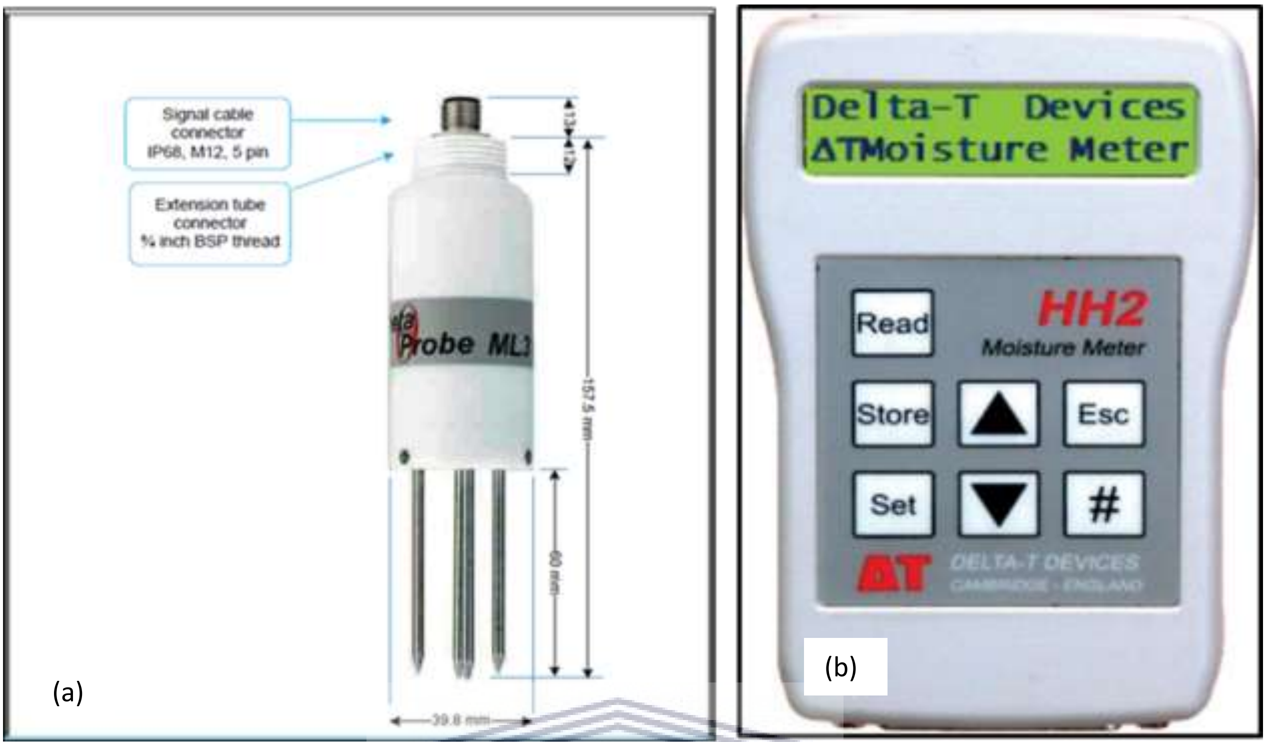

Figure 6.8: (a) ML3 ThetaProbe for measuring soil water content (b) HH2 meter for reading soil water content

In each land use/cover type (for instance grazed land), 10 monitoring sites for measuring soil water were selected. For each monitoring site, soil water for each sampling time, was taken at 5 depths making the number of samples taken from each land use/cover type to be 50 (i.e. 5 x 10). This was repeated for all other land use/cover types. The soil water content measurements were taken after every two weeks starting from October 2015 to December 2015 (during the short rains), January to March 2016 (during the dry season) and from March to June 2016 (during the long rains). The wet and dry seasons were selected so as to assess the soil water content over a wet and dry season.

Surface runoff measurements

A 3 x 2 m plot was used for measuring surface runoff from each land use/cover type for the purpose of comparing runoff in the farm lands (crop and grazed) with that from undisturbed land (forest and wooded grassland). The size of the experimental plots was based on studies that indicate that results from small size plots such as 1m x 1m were comparable to those of the larger plots (10 m x 1m). For instance a study by Battany and Grismer (2000) suggested that the results from small plots ($1m^2$) could be comparable to those of large plots (30-40 m^2). Bagarello et. al. (2011) concluded that plot width and length did not have a statistically significant effect on the mean surface runoff rate. Similarly, Thomaz and Vestena (2012) on the scale effect on runoff volumes and soil loss in

Brazil found that there was no significant difference between the soil loss in 1 m^2 and 10 m^2 plots. Based on these studies a 3 m x 2 m plot was used and the runoff measured was converted to depth (in mm).

At the start of the experiment in October 2015, the farms where the runoff plots were prepared had been ploughed and planted by farmers with maize (Zea mays) in lines spaced at 75 cm (row to row) x 45 cm (hole to hole) following the common agricultural practices in this area. During the experimental period, weeding for the crops within the runoff plots was done by hand; first 3 weeks after the seeds germinated and second weeding was done 7 weeks after germination. The grazing land was covered by grass and the farmers reared an average of four cows on a hectare of land.

For all the plots the sides were surrounded by a 45 cm wide and 30 cm high compacted soil bands to prevent runoff from outside flowing into the plot. The surrounding of the plot sides with compacted soil bands did not interfere with the surface runoff measurements since rain was falling inside the plot. The plot boundaries were inspected regularly especially after a rainfall storm and were repaired when necessary. At the lower end of the plot, a collector trench was dug and lined with a 0.4 mm thick plastic sheet to harvest runoff. The collector trench was 2 m long, 0.5 m wide and 0.5 m deep. A portable roof made of 0.4 mm thick plastic sheet was placed on top of every collector trench in order to keep off the rain water from entering into the collector trench. Diversion ditches were dug upslope and on the sides of the plot to intercept and divert the runoff (Figure 6.9). Runoff collected in the trench was measured every day in litres. The runoff in litres was then converted to depth in mm (by dividing the total runoff from the plot by the plot area) to correspond with the rainfall measurements. The limitation of the plot study was that the measurements of surface runoff were done manually and on daily basis. Therefore, the method did not separate the effects of storm rainfall on surface runoff in all the plots.

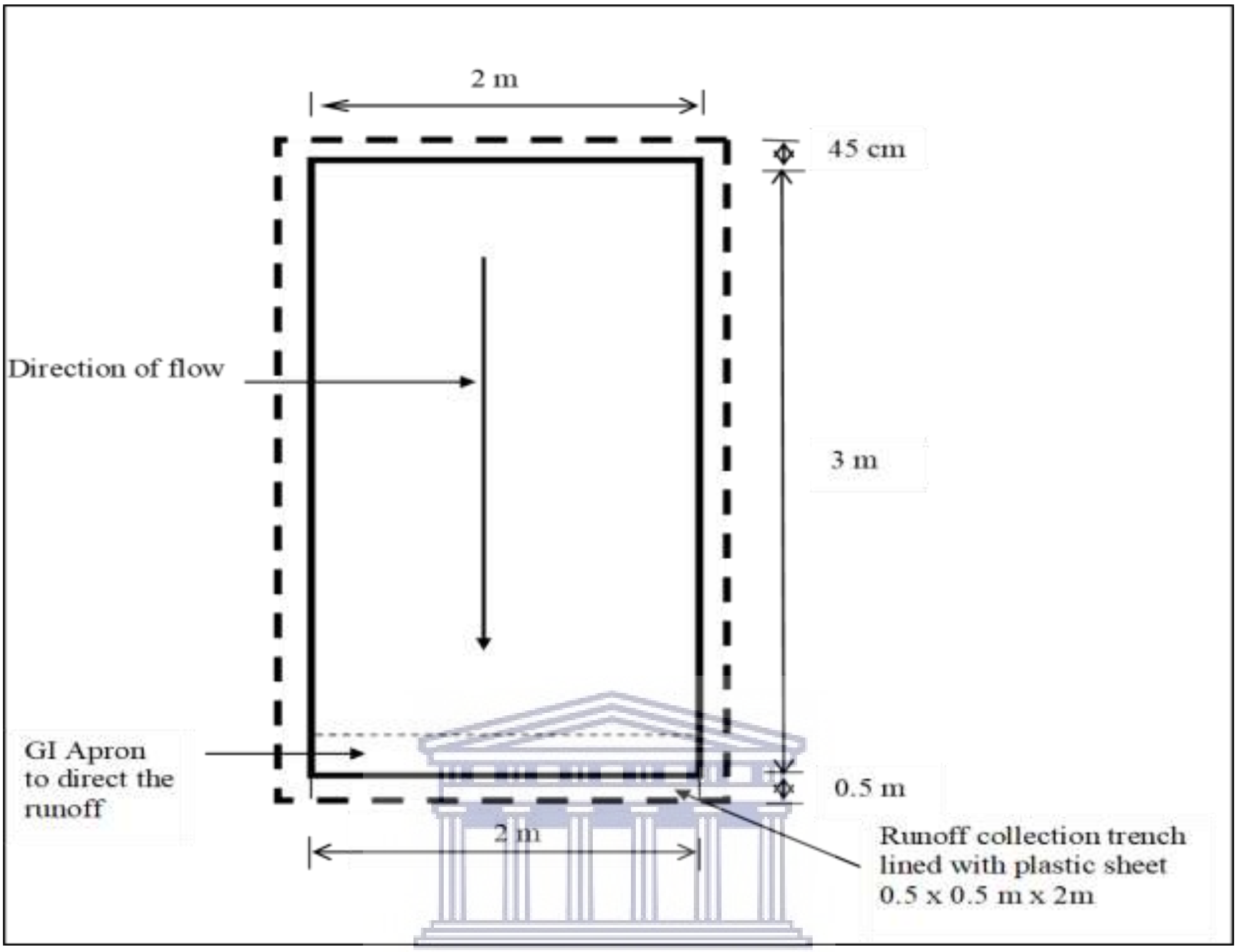

Figure 6.9: Design of plots for collecting surface runoff

6.2.4 Data analysis

Descriptive statistics (mean and standard deviation) were used in analysing the rainfall and soil properties such as the mean soil properties in different land use/cover types and at various depths, and comparing the soil infiltration rates. The linear regression was used in comparing the rainfall events and monthly rainfall, and in the calibration of the ML3 ThetaProbe with the oven dry soil water content.

The measured soil water variables were derived as follows:

Suppose that the soil water content of sampling site (*i*), at depth (*j*), in a particular land use/cover type is expressed as SW_{jk}; then, mean soil water content at that depth at each sampling time *k* is:

$$SW_{jk} = \frac{1}{10}\sum_{i=1}^{i=10} \mathrm{SW}ci \qquad (6.1)$$

where SWci is soil water content for a sampling site *i*; i= 1…..10.

The mean soil water content for each land use/cover for the sampling period is derived as:

$$\mathrm{SW}_{cj} = \frac{1}{20}\sum_{k=1}^{k=20} SW_{jk} \qquad (6.2)$$

Where SW_{cj} is the mean soil water content over the sampling period at the depth j; k is the sampling time (k =1-20). Note that soil water content for each land use/cover was sampled at five depths (i.e. j =1-5)

6.2.5 Soil water modelling

Soil water contents were simulated for croplands, grazed, wooded grassland and forest lands with Hydrus - 1D, 4.16 software package (Šimůnek et. al., 2016). Hydrus -1D is a one-dimensional saturation-unsaturated soil water model that simulates soil water dynamics by numerically solving the Richard's equation (Equation 6.3) (Radcliffe & Šimůnek, 2010). The purpose of soil water modelling was to simulate daily soil water content for determining the spatial and temporal variability of soil water across the different land cover types. It was necessary to model soil water since the *in situ* measurements were not taken continuously and therefore not able to adequately capture the effects of land use/cover to soil water content during wet and dry seasons. The modelling of soil water content was also important to provide daily soil water data to be used in determining the effects of soil water on runoff.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\left(\frac{\partial h}{\partial x}+1\right)\right] - S(h) \qquad (6.3)$$

where θ is the volumetric soil water content (L^3/L^3), t is the time (T), x is the vertical space coordinate (L), K is the hydraulic conductivity, h is the water pressure head (L) and $S(h)$ is a water sink term accounting for root water uptake (L^3/L^3.T).

The soil hydraulic properties for the unsaturated zone were represented by the parameters given by Van Genuchten, (1980)

$$\partial(h) = \begin{cases} \theta_r + \frac{\theta_s-\theta_r}{[1+|\propto h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (6.4)$$

$$K(h) = K_s S_e^l \left[\left(1 - S_e^{1/m}\right)^m\right]^2 \qquad (6.5)$$

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad (6.6)$$

where θ_r and θ_s are the residual and saturated water contents (L^3/L^3), respectively, K_s is the hydraulic conductivity (L/T^1), S_e is the effective saturation, α (L^{-1}), and l and n are the empirical shape parameters (the inverse air entry point, pore connectivity, and pore size distribution parameters, respectively),

$$m = 1 - 1/n \tag{6.7}$$

The sink term S (h) in Equation (6.4) is the volume of water removed from a unit volume of soil per unit time by roots of plants. It accounts for actual root water uptake equal to the actual transpiration that is calculated in the model using an equation by Feddes et. al. (1978) written as:

$$S(h) = \alpha(h)\,Sp \tag{6.8}$$

Where α (h), the root-water uptake stress response function is a prescribed dimensionless function of the soil water pressure head ($0 \leq \alpha \leq 1$), Sp is the potential water uptake rate (T^{-1}). Root water uptake is assumed to be zero close to saturation. Water uptake is also assumed to be zero at wilting point pressure head. Therefore, water uptake increases or decreases linearly with h. Variable Sp is equal to the water uptake rate during period of no water stress when $\alpha(h) = 1$.

Due to the high porosity (porosity > 50 %) of the soil that was observed in this catchment, the horizontal movement of water in the soil was assumed to be negligible. The model was then run at a daily time step and the model was used to simulate the soil water movement processes in the 0-70 cm soil layers that supports most of the crops grown in the area such as maize, beans, grass and tea. The upper boundary was set to the atmospheric boundary with the surface layer which permits water to build up on the soil surface. The lower surface was set for free drainage conditions due to the deep soil in the study area where the water table is much deeper than the last layer that was reached during the study period.

Hydrus -1D required the input of meteorological parameters such as rainfall, potential soil surface evaporation (E_p mm/day); defined as the rate of evaporation from a surface of water and potential transpiration (T_p mm/day); defined as water loss often expressed as a rate of flux by a plant when soil is not limiting. Daily rainfall was input into the model. The method used for calculating ET was the FAO-Penman-Monteith (Allen et. al., 1998) with data obtained from a station near the study area. The meteorological data sets required for estimating ET were maximum and minimum temperatures, wind speed, solar radiation and relative humidity. The Leaf Area Index (LAI) for different land use/cover types needed for estimating evaporation and transpiration were obtained from MODIS satellite images. MOD15A2 satellite images were downloaded from the USGS website: https://lpdaac.usgs.gov.

The T_p and E_p were calculated in Hydrus -1D using the following equations:

$$T_p = ET_o\lceil 1 - e^{-k.LAI}\rceil = ET_oSCF \quad (6.9)$$

$$E_p = ET_o e^{-k.LAI} = ET_o\lceil 1 - SCF\rceil \quad (6.10)$$

where *LAI* is the leaf area index (dimensionless) that was assumed to be 3.2 for maize that is half-way grown, 2.0 for the grass (Chen et. al., 2014) and 6.6 for the forest. These values are similar to those used by Dovey et. al. (2011). *SCF* is the soil cover fraction (dimensionless) that was calculated in Hydrus-1D based on *LAI* for a particular land cover, and *k* (dimensionless) is the radiation extinction coefficient by the canopy; for maize and grass this coefficient was taken as 0.463 (Ritchie, 1972) and that of the trees was taken as 0.4 similar to that used by Dovey et. al. (2011). The rainfall interception for cropland was as assumed to be 2.5 mm/day and for the forest 4.0 mm/day following guidelines provided by Liu de Smedt (2004) and Gerrits (2010) as cited in (Kiptala, 2020).

Model calibration

In model calibration, Hydrus-1D implements a Marquardt-Levenberg type parameter estimation technique (Marquardt, 1963; Šimůnek & Hopmans, 2002) for inverse estimation of soil hydraulic, solute transport, and /or heat transport parameters from measured transient or steady-state flow and/or transport data.

The objective function Φ to be minimized during the parameter estimation process using Hydrus -1D is defined in Equation (6.11) (Šimůnek et. al., 1998a):

$$\Phi\lceil b,q,p\rceil = \sum_{j=1}^{mq} v_j \sum_{i=1}^{n_{qj}} w_i,j\left\lceil q_j^*\left(x,t_j\right) - q_j\left(x,t_j,b\right)\right\rceil^2 + \quad (6.11)$$

$$\sum_{j=1}^{mp} v_j \sum_{i=1}^{n_{pj}} w_{ij},\left\lceil p^*j(x,\theta_i) - p_j(x,\theta_i\,,b)\right\rceil^2 +$$

$$\sum_{j=1}^{n_b} \tilde{v}_j \left\lceil b_j^*(x) - b_j(x)\right\rceil^2$$

where $\Phi\lceil b,q,p\rceil$ is the left side of the equation representing objective function Φ, and b,q,p representing the variables such as $\theta_r, \theta_s, \alpha,$ n and Ksat considered which are optimized in order to get the best variables for the soil water modelled.

The first term on the right side represents deviations between measured and calculated space time variables. In this first term, mq is the number of different sets of measurements, n_{qj} is the number

of measurements within a particular measurement set, $q_j^*(x, t_j)$ represents specific measurements at time t_j for the jth measurements set at location x, $q_j(x, t_j, b)$ represent the corresponding model predictions for the vector of optimized parameters ***b***, (e.g. soil hydraulic, heat transport, and /or solute transport and reaction parameters), and v_j and $w_i j$ are weights associated with a particular measurement set or point, respectively. The second term on the right side represents differences between independently measured and predicted soil hydraulic properties (e.g. retention θ(h) and /or hydraulic conductivity,
$K\theta$ or $K(h)$, data) for different soil horizons (x) , while the terms mp, n_{pj}, p^*j $(x, \theta_j), p_j(x, \theta_i, b)$, $\tilde{v}_j$ and $w_i j$ have similar meanings as for the first term but are now for the soil hydraulic properties. The last term represents a penalty function for deviations between prior knowledge of the soil hydraulic parameters $b_j^*(x)$, and their final estimates, $b_j(x)$, with n_b being the number of parameters with prior knowledge and v_j representing pre-assigned weights.

Hydraulic parameters in Hydrus -1D were based on the Rosetta pedotransfer function (Schaap et. al., 2001) that are based on measured soil particle size distribution (percentage of clay, silt and sand) including bulk density. During calibration, the variables that were changed were the saturated hydraulic conductivity (k), alpha (α), n and both the saturated (θ_s) and residual water (θ_r) contents and the l term. Few parameters were optimized at a time since Hydrus-1D model could only optimize 15 parameters at a time. Following guidelines from Jacques et. al. (2002) as cited in González et. al. (2015), the parameters were fitted one at a time to minimize equifinality.
The model calibration was ascertained using the following goodness of fit statistical indicators: the coefficient of determination R^2 (Equation 6.12), and the root mean square error (RMSE) (Equation 6.13). The R^2 describe the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with value greater than 0.5 indicating acceptable results.

$$R^2 = \frac{\left[\sum_{i=0}^{n}(sw_i - \overline{sw})(swp_i - \overline{swp})\right]^2}{\sum_{i=1}^{n}(sw_i - \overline{sw})^2 \sum_{i=1}^{n}(swp_i - \overline{swp})^2} \qquad (6.12)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}[sw_i - swp_i]^2}{N}} \qquad (6.13)$$

where sw_i and swp_i are the measured and predicted soil water content values respectively, $\overline{sw}$ and $\overline{swp}$ are the mean of soil water values respectively, and n and N are the number of observations.

6.2.6 Seasonal variations of vertical soil water content in different land use/cover types

In order to understand the seasonal variations of the vertical soil water content in different land use/cover types, the simulated soil water was used. Note that the measured soil water data was used to calibrate the Hydrus-ID model. The seasons considered were September, October and November (SON) for the *short rains*, December, January and February (DJF) dry season (which was wet season during the time of the study) and the March, April and May (MAM) *long rains*. In every land use/cover, the mean daily soil water at specified soil depths (0-5 cm, 10-15 cm, 25-30 cm, 40-45 cm and 65-70 cm) was calculated and plotted against the soil depth for each season. The same seasons SON, DJF and MAM were also used to determine the variability of soil water during the extreme of highest soil water (in the forest) and extreme of lowest soil water (in the cropland) in different soil depths. In order to get the soil water variability in these seasons the soil water in the cropland (lowest) was subtracted from that of the forest (highest).

6.2.7 Runoff

Runoff from the plots (3 m x 2 m) was analysed using the runoff coefficient (RC) method. This RC gives the amount of rainfall that becomes runoff in each land use/cover type. This method is widely used at plot scale (Descheemaeker et. al., 2006; Taye et. al., 2013; Berihun et. al., 2019). The plot-scale RC (%) values were computed by dividing the runoff yield (R_p mm) by the corresponding rainfall depth (P, mm) for each plot i using Equation (6.14); R_p is the measured surface runoff yield (mm) at plot i calculated by dividing the runoff volume measured at the collection trench by the runoff plot area (3 m x 2 m). Note that the RC values were computed (for each plot) for each day that there was sufficient rainfall to produce runoff.

$$RC_i = \frac{R_p}{P} x100 \tag{6.14}$$

The RC_i for each land use/cover was averaged over all the ten plots to give a representative value for a given day.

t-statistic

The t-statistic was used in comparing the temporal soil water content at various depths for the different land use/cover types and also to compare runoff from different land use/cover types.

The coefficient of determination (R^2) was used to correlate variability of soil water or runoff to rainfall and also to compare the influence of soil water content on runoff.

6.3 Results

6.3.1 Rainfall

The mean monthly rainfall depths from the HOBO Rain-gauges RG3-M was 134.73 mm/month from 01/08/2015 to 01/07/2016 that was relatively more than the mean monthly rainfall of the long-term (1980- 2009) average that was 117.53 mm/month from rainfall stations within the catchment. For instance, at Merigi the rainfall depth for the month of November 2015 was 327.6 mm/month compared to the rainfall depth of 142.28 mm/month in November (1980-2009). Likewise, the total rainfall for the month of April at the rain-gauge was 226.2 mm compared to 212.84 mm for April (1980-2009) (Figure 6.10). The high peaks of rainfall in November and April during the study period suggests that the rainfall during the 2015/2016 period was higher than the long term mean.

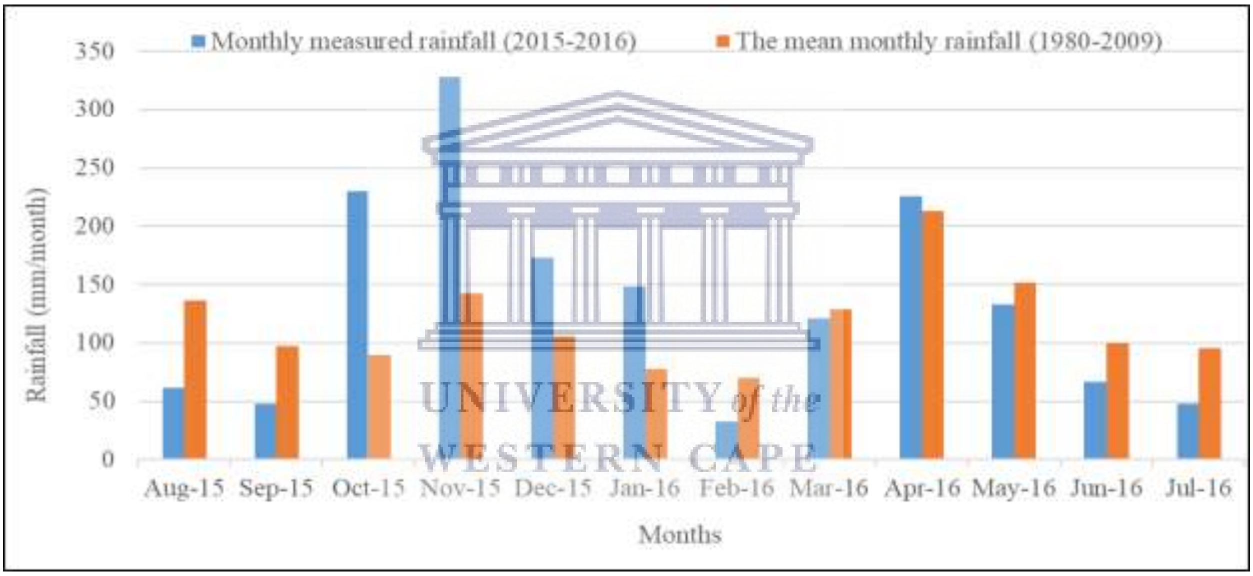

Figure 6.10: Averaged monthly rainfall depth distribution for Merigi and Kirenget for 2015-2016 and the spatial average of the long term rainfall depths (1980-2009) for Bomet, Nyangores and Kiptunga rainfall stations located in the catchment. Note: The rainfall for Merigi and Kirenget were measured during the study period using the Hobo raingauge.

During the study period (October 2015 to June 2016) the total rainfall in Nyangores River Catchment was 1369.2 mm that was contributed by 875 rainfall events. Out of the total number of rainfall events, 93 % (815) had an intensity of less than 6mm/hour. However, the small percentage (7%) of the larger rainfall events contributed more of the total rainfall (53 %) (Table 6.2). This implies that even if rainfall caused by rainfall intensities less than 6mm/hour was more frequent, larger rainfall events (>6mm/hour) were more significant in determining soil water and runoff.

Table 6.2: Rainfall intensity for the various rainfall events for the period October 2015 to June 2016

Intensity (mm/hr)	No. of rainfall events	Proportion of rainfall events (%)	Rainfall amount in (mm)	Proportion of total Rainfall depths (%)
<6	815	93.14	647.40	47.28
6-12	38	4.34	317.80	23.21
12-18	14	1.60	193.80	14.15
18-30	6	0.69	143.00	10.44
30-60	2	0.23	67.20	4.92
Total	875	100.00	1,369.2	100.00

The number of rainfall events aggregated on monthly basis showed a linear relationship with monthly rainfall with an $R^2 = 0.75$ (Figure 6.11). The study period was characterized by low inter-seasonal rainfall variability with a coefficient of variation of 0.4. This implies that the soil water and runoff respectively were not expected to differ significantly across the months during the study period.

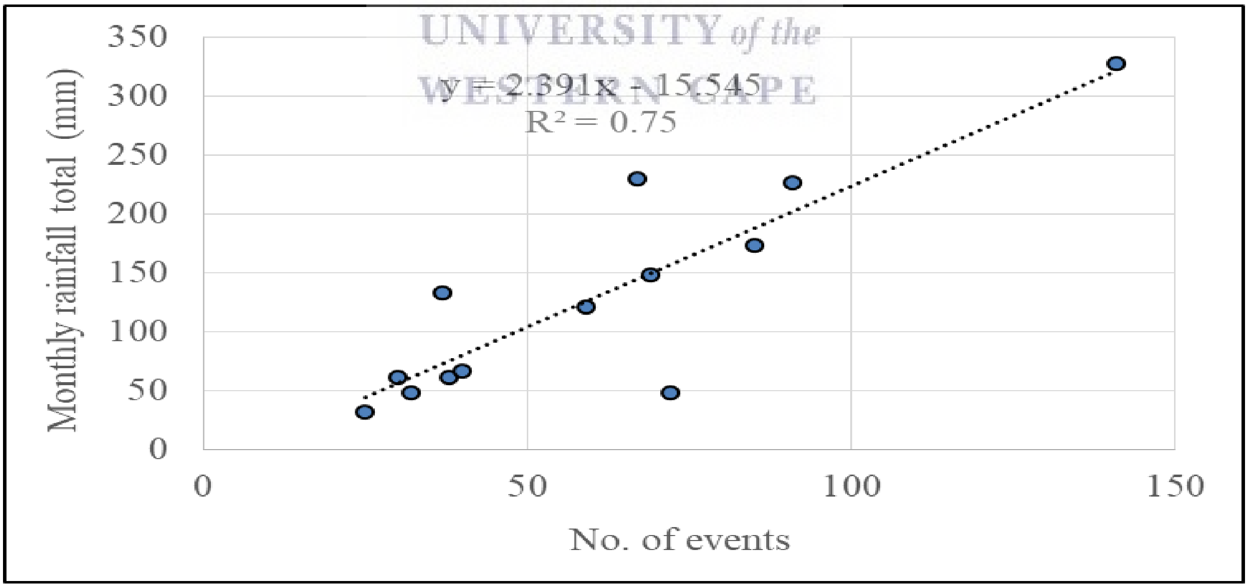

Figure 6.11: Frequency of rainfall event against total monthly rainfall depth

6.3.2 Soil properties

The dominant soil texture in all the land use/cover types (cropland, grazed, wooded grassland and forest) was clay. The mean soil bulk density was highest in the cropland (1.17 g cm^{-3}) and lowest in the forest (0.98 g cm^{-3}). The forest had the highest soil organic carbon (SOC) while the lowest was observed in the cropland. The mean porosity of the soils was highest within the forest while the cropland, grazed and wooded grasslands had relatively the same. Hydraulic conductivity (*K*) was highest in the forest while the wooded grassland had the lowest. The soil infiltration was highest in the forest cover (89.4cm/hr) and grazed land showed the lowest (25.3cm/hr) (Table 6.3). The cumulative infiltration rate of the forest was 2.8 times more than that of the cropland and 3.5 times that of grazed land. These results imply that cultivation and grazing activities have resulted in slower infiltration rate. Infiltration in all the land use/cover types stabilized after 150 minutes (Figure 6.12). The differences in the soil properties would influence soil water content in each land use/cover type.

Table 6.3: Mean soil properties in different land use/cover types

Land use/ cover type	**BD (g cm^3)**	**SOC (%)**	**Sand (%)**	**Clay (%)**	**Silt (%)**	**P (%)**	**K (cm/hr)**	**I (cm/hr)**
Cropland	1.17 (± 0.07)	0.68 (± 0.03)	17.6 (± 1.67)	57.2 (± 3.63)	25.20 (± 3.63)	61.14 (± 2.99)	2.90 (± 0.09)	31.4 (±2.89)
Grazed land	1.10 (± 0.04)	1.90 (± 0.99)	17.20 (± 1.8)	52.00 (± 10.71)	30.80 (± 5.8)	61.54 (± 3.02)	2.51 (± 1.95)	25.3 (±1.36)
Wooded grass land	1.01 (± 0.10)	2.09 (± 1.11)	21.60 (± 6.07)	52.40 (± 10.71)	26.00 (±7.07)	61.29 (± 4.34)	2.04 (± 0.06)	34.9 (±2.15)
Forest land	0.98 (± 0.04)	2.68 (± 1.04)	18.04 (± 2.61)	50.01 (± 2.45)	31.60 (±2.97)	70.92 (± 8.36)	3.71 (± 0.05)	89.4 (±2.69)

BD = Bulk density, SOC = Soil organic carbon P=Porosity I =Infiltration K = Hydraulic Conductivity

Note: The values in parentheses are Standard Deviations

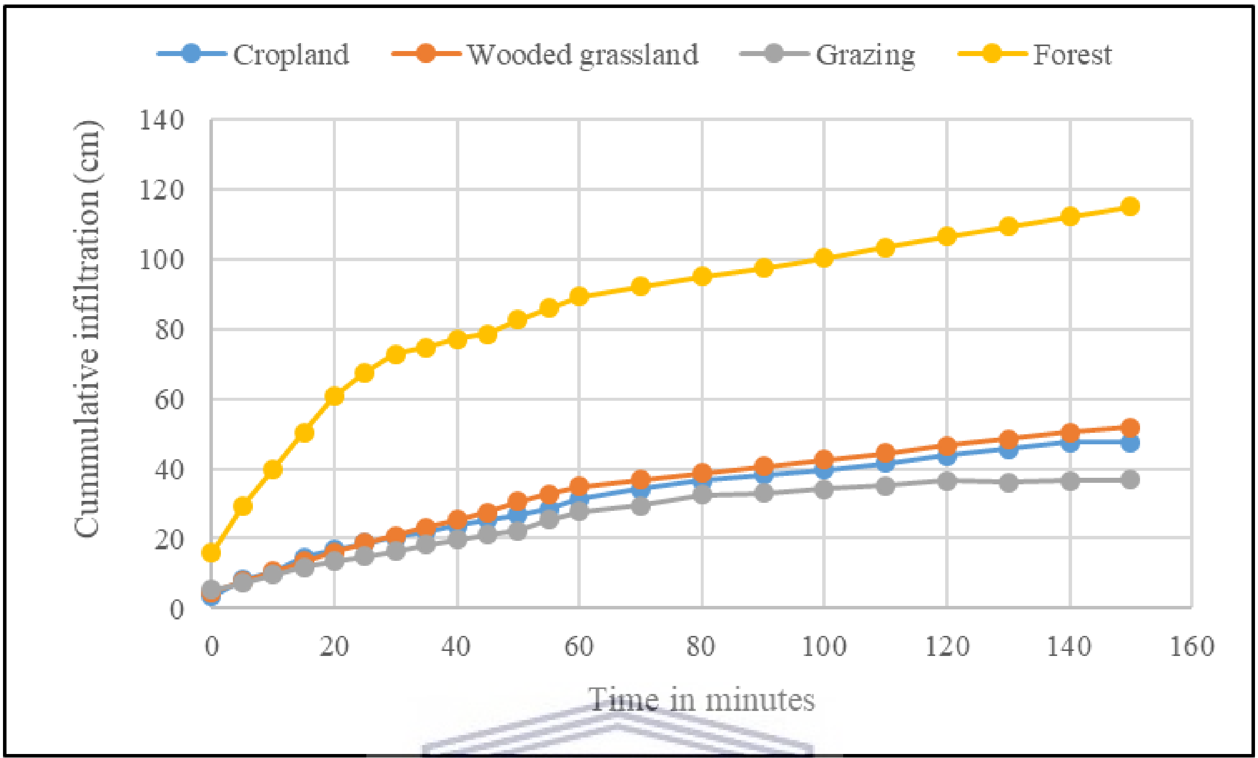

Figure 6.12: Cumulative infiltration curves for soils in different land use/cover types

6.3.3 Measured and simulated soil water

Calibration of ML3 ThetaProbe

The ML3 ThetaProbe was calibrated using gravimetric water content measurements. Results showed that the soil water content measured using the gravimetric method compared well with the field measured soil water content by ML3 ThetaProbe ($R^2 = 0.9$) (Figure 6.13). Therefore, ML3 ThetaProbe was found to be adequate for measuring the field soil water content needed to calibrate the Hydrus-1D model.

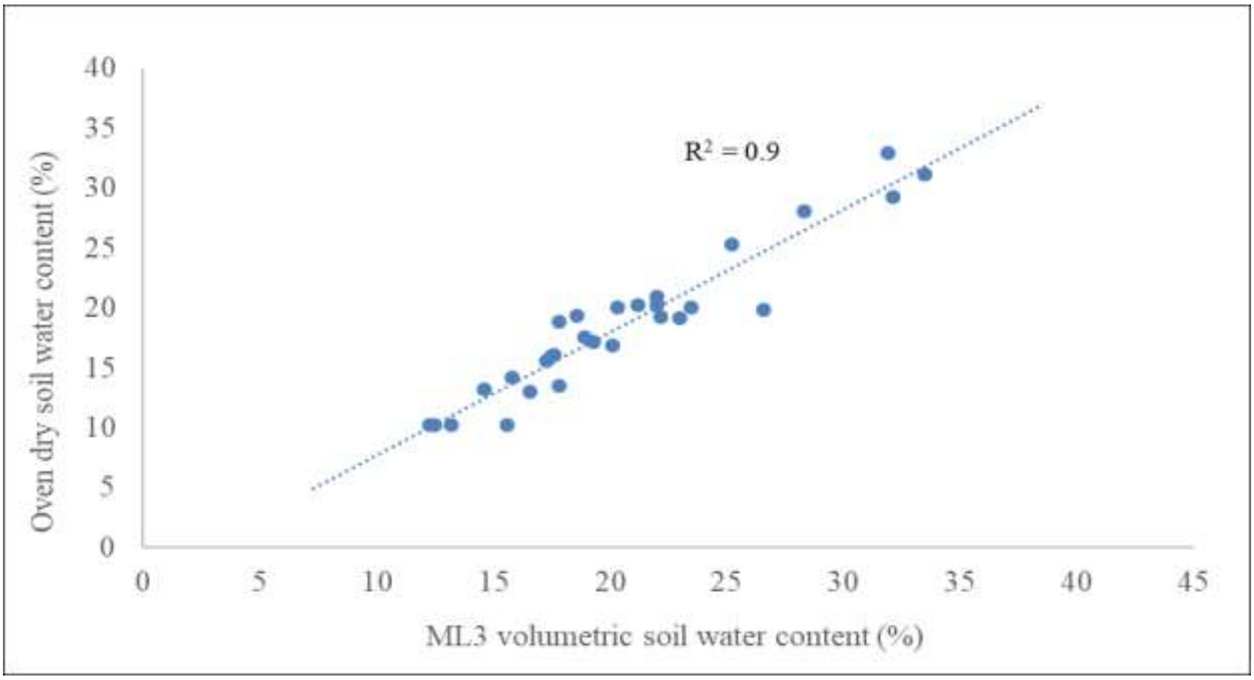

Figure 6.13: Calibration of ML3 ThetaProbe using regression analysis

Simulated soil water with Hydrus -1D model

The soil water content in each land use/cover type was measured at various depths at an interval of two weeks during the period October 2015 to June 2016. In order to improve the temporal resolution of the data, the Hydrus -1D model was set up and calibrated using the measured soil water data. The simulated daily data had a moderately good agreement with the observed data ($R^2 > 0.5$) for most of the soil layers. The RMSE were very close to zero in all the land use/cover types (Figures 6.14-6.18). Generally, the first two layers (0-5 cm and 10-15 cm) of the soil were simulated better than the rest of the layers. The simulation demonstrates that when meteorological variables and soil properties are available, soil water in a sub-humid catchment such as the Nyangores River Catchment can adequately be estimated using Hydrus-1D.

Considering the variability of the simulated soil water in the 0-5 cm soil layer in each land use/cover type, the results showed that the cropland and grazed land had less soil water content than the wooded grassland and forest in all days over the simulation period. (Figure 6.14). In this layer the simulated soil water showed a high value at around the 200th day from the start of the soil water monitoring experiments (20th October 2015) in the cropland, grazed and the wooded grassland which were attributed to heavy rainfall (greater than 40mm/day) that was experienced in the catchment about this time. The lack of the similar peak in the forest was attributed to the shading by the tree canopy.

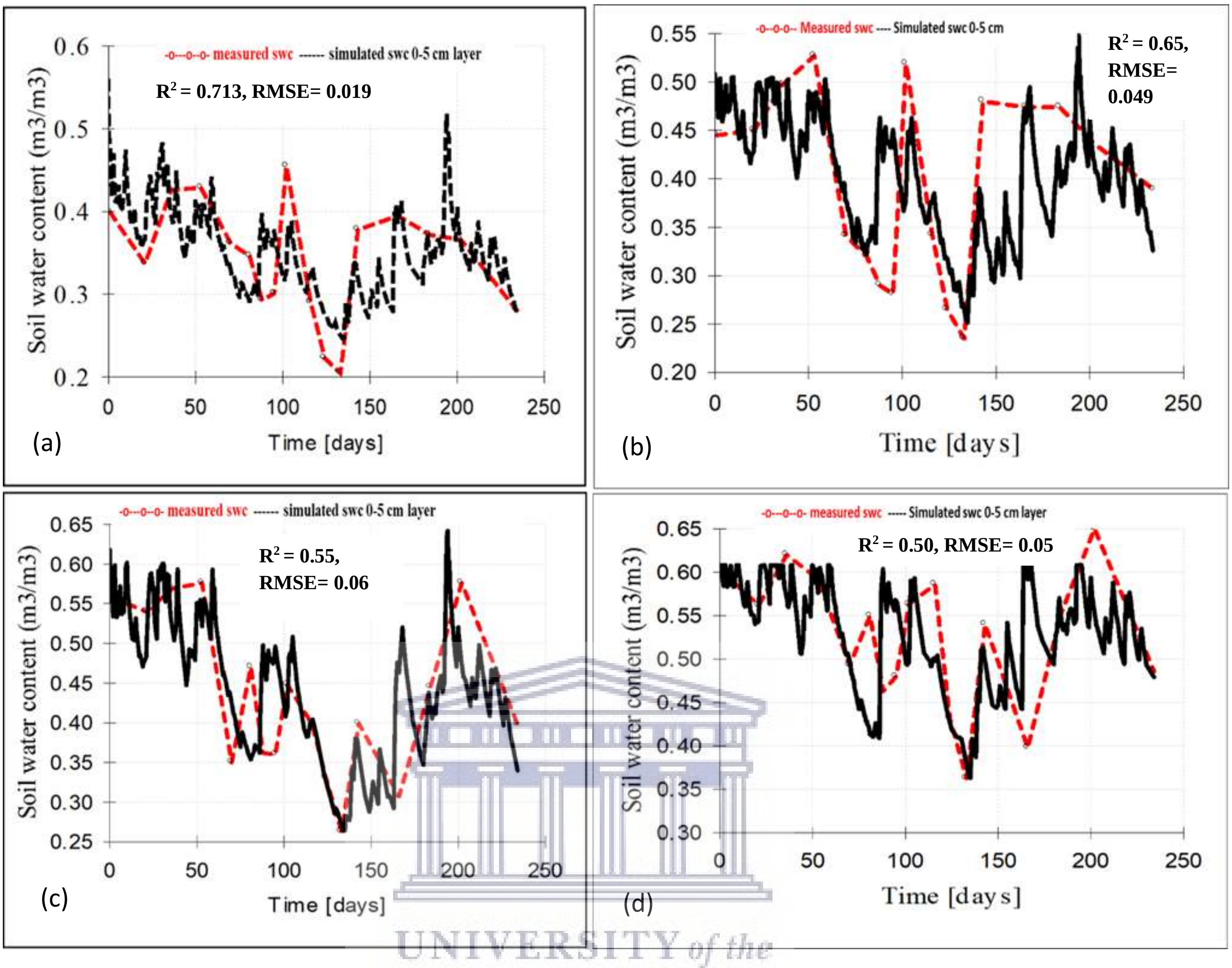

Figure 6.14: The temporal variability of soil water content simulated and measured in the 0-5 cm layer of soil in different land use/cover types (a) cropland (b) grazed land (c) wooded grassland (d) forest land.

The simulated soil water content in the 10-15 cm soil layer showed a similar pattern to the 0-5 cm soil layer in all the land use/cover types with shorter peaks at the 200th day from the start of experiments (Figure 6.15). The short peaks noted here were attributed to the delay in the soil water reaching the peak after the rainfall.

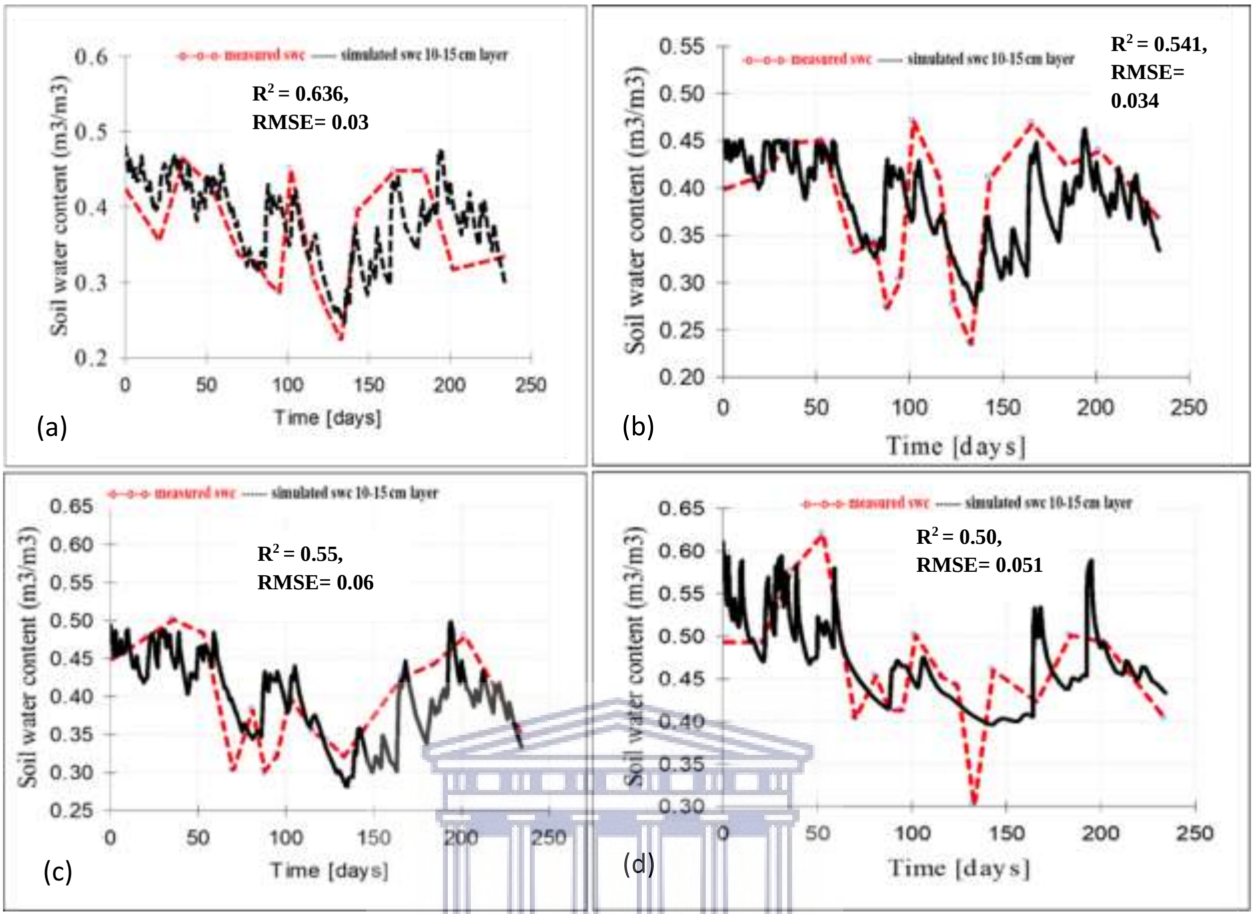

Figure 6.15: The temporal variability of soil water content simulated and measured in the 10-15 cm layer of soil in different land use/cover types (a) cropland (b) grazed land (c) wooded grassland (d) forest land.

In the 25-30 cm soil layers, the simulated soil water does not show much fluctuations between the highest and the lowest soil water content in the different land use/cover types as was the case in the 0-5 and 10-5 cm soil layers (Figure 6.16). The minor changes could be attributed to the influence of clay soil layers on downward movement of soil water. However, the peaks of soil water were similar to those in the preceding layers.

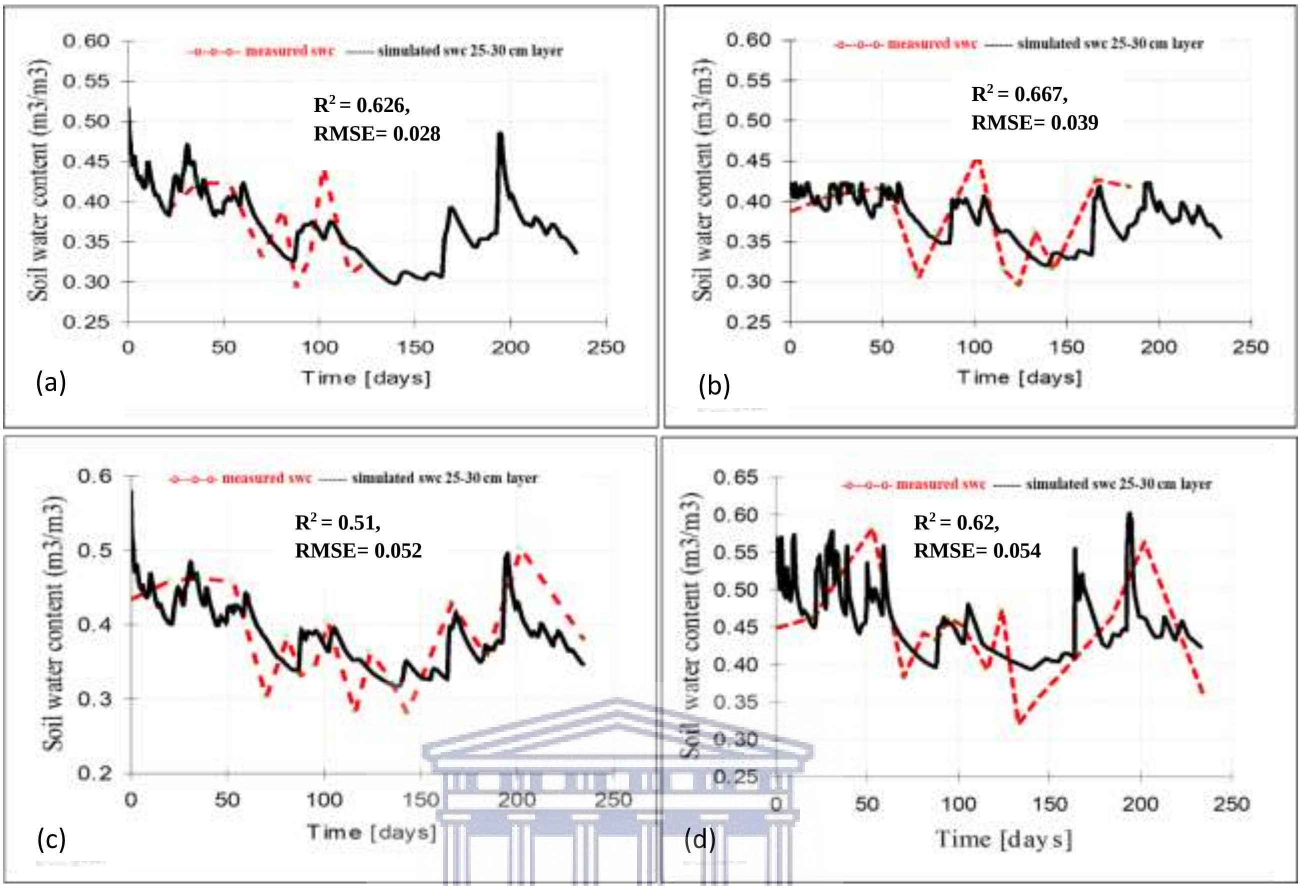

Figure 6.16: The temporal variability of soil water content simulated and measured in the 25-30 cm layer of soil in different land use/cover types (a) cropland (b) grazed land (c) wooded grassland (d) forest land.

For the layers 40-45 cm and 65-70 cm there is not much difference in soil water content across all the land use/cover types. In each land use/cover type the soil water content varied between 0.45 m^3/m^3 0.35 m^3/m^3 (Figure 6.17 & 6.18). These results depict that the amount of soil water in this layer among the land use/cover types is the same. This was attributed to the fact that the cultivation and grazing activities do not influence movement of water at this layer.

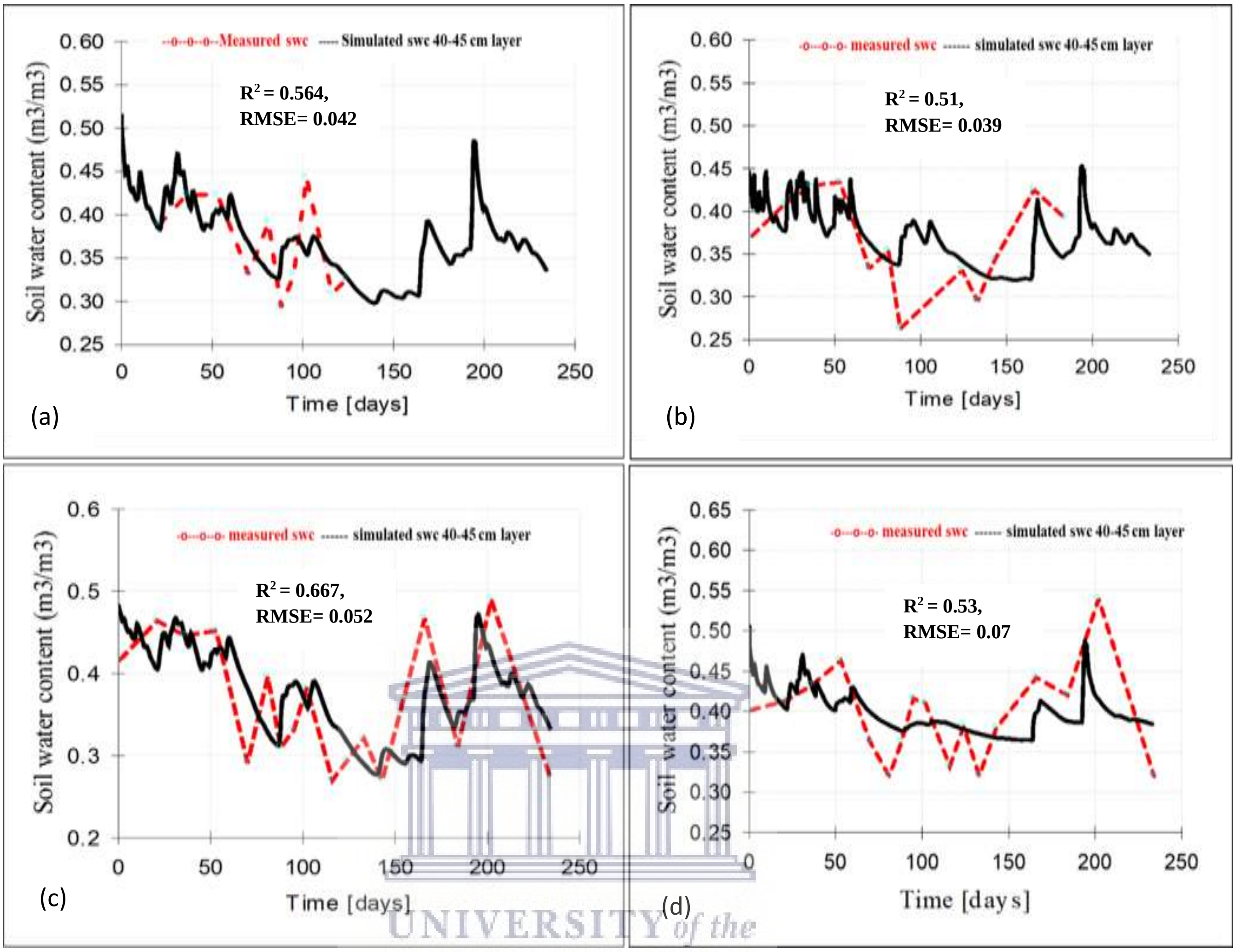

Figure 6.17: The temporal variability of soil water content simulated and measured in the 40-45 cm layer of soil in different land use/cover types (a) cropland (b) grazed land (c) wooded grassland (d) forest land.

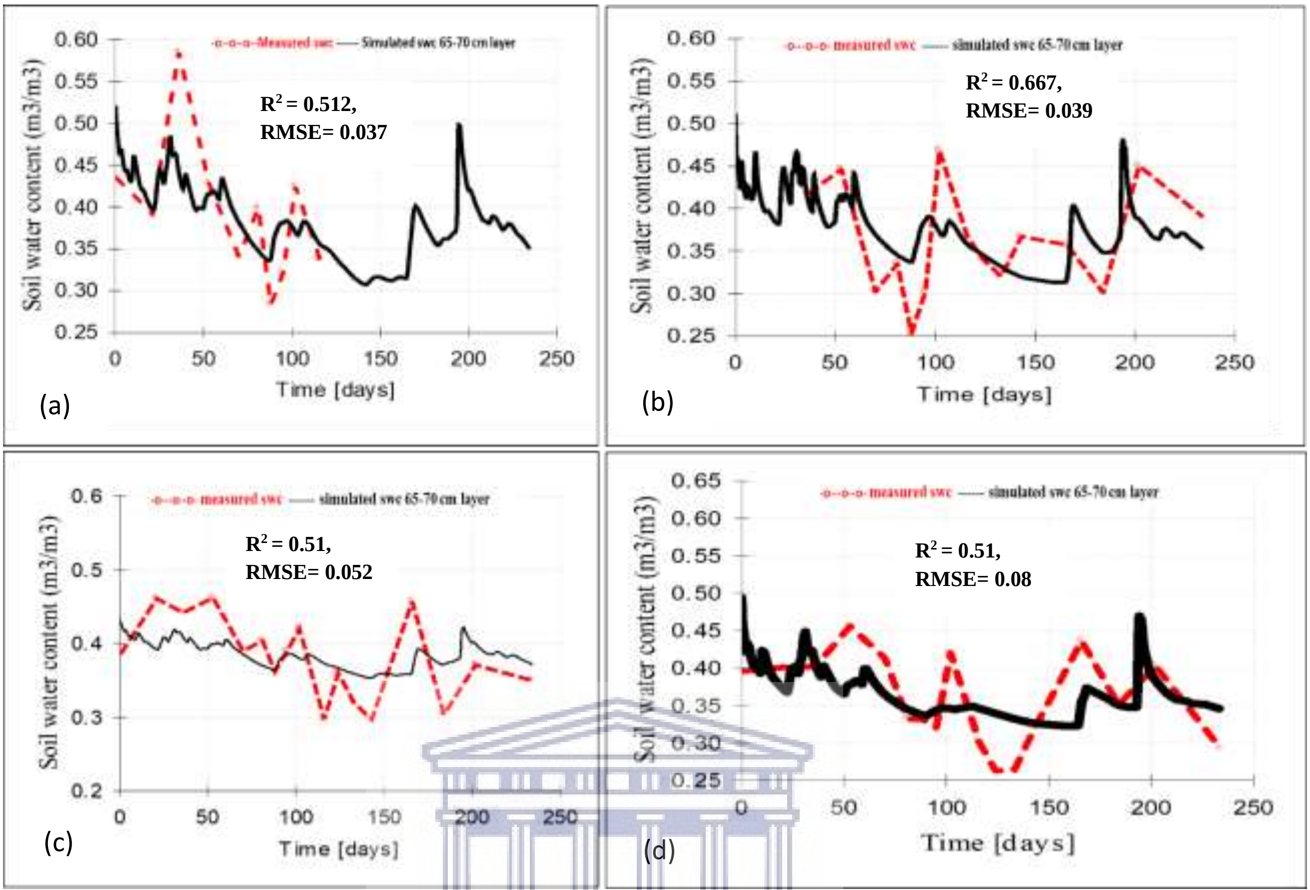

Figure 6.18: The temporal variability of soil water content simulated and measured in the 65-70 cm layer of soil in different land use/cover types (a) cropland (b) grazed land (c) wooded grassland (d) forest land.

Comparison of soil water content in different land use/cover types

In this section the simulated soil water from the cropland and grazed lands (land use/cover types that were converted from either forest or the wooded grasslands) at each depth, was compared to the soil water of the wooded grassland and forest (undisturbed land) respectively. The results showed that mean soil water in the cropland was statistically significantly less than that of the grazed land, wooded grasslands and forest respectively for the soil layer from 0-30 cm depth ($p< 0.05$). However, for the depths 40-70 cm, the observed differences were significant between soil water in the cropland and the forest and also between cropland and the grazed land (Table 6.4). The lower soil water content observed in both the cropland and the grazing lands particularly at 0-30 cm layers were attributed to exposure of the soil to heating by the sun causing higher evaporation. Compaction through trampling by animals and farm machinery also reduces movement of water into the soil. These soil water variations were also attributed to the observed differences in soil properties (see Table 6.3 above); for instance, the high bulk density and lower SOC experienced in the cropland have the potential to lower the soil water content.

Table 6.4: Comparison of simulated soil water content in different land use/covers for various depths; CL= cropland, GZ= grazed land, WGS= wooded grassland, FT= forest.

Soil depth	Land use/cover type	Land use/cover mean (μ) (m^3/m^3) of simulated soil water content		t-statistic	p-value
0-5cm	CL-GZ	CLμ = 0.391	GZμ = 0.556	-38.13	0.000*
	CL-WGS	CLμ = 0.391	WGSμ = 0.491	-12.05	0.000*
	CL-FT	CLμ = 0.391	FTμ = 0.557	-61.97	0.000*
10-15cm	CL-GZ	CLμ = 0.411	GZμ = 0.475	-20.48	0.013*
	CL-WGS	CLμ = 0.411	WGSμ = 0.431	-7.33	0.000*
	CL-FT	CLμ = 0.411	FTμ = 0.609	-156.2	0.000*
25-30cm	CL-GZ	CLμ= 0.371	GZμ = 0.378	-3.99	0.000*
	CL-WGS	CLμ = 0.371	WGSμ = 0.389	-9.18	0.000*
	CL-FT	CLμ = 0.371	FTμ = 0.451	-37.17	0.000*
40-45cm	CL-GZ	CLμ= 0.369	GZμ = 0.373	-1.42	0.158
	CL-WGS	CLμ= 0.369	WGSμ = 0.371	-1.99	0.060
	CL-FT	CLμ = 0.369	FTμ = 0.398	-2.92	0.023*
65-70cm	CL-GZ	CLμ= 0.379	GZμ – 0.374	-3.35	0.000*
	CL-WGS	CLμ = 0.379	WGSμ = 0.388	-1.56	0.156
	CL-FT	CLμ= 0.379	FTμ = 0.362	-1.26	0.013*

***Soil water content is significant at p<0.05**

The vertical variability of soil water content in different land use/cover types was examined by considering the wet (MAM& SON) and dry (DJF) seasons using the simulated soil water content. In each season the soil water content first increases with depth up to about 15 cm and then decreases up to 25 cm. Beyond 25 cm the soil water content does not vary significantly with depth for all land use/ cover types (Figure 6.19). These results show that soil water depicted similar patterns during the wet and dry seasons. This could be attributed to the fact that there was substantial rainfall during the study period in the dry season that resulted to similarity in the way water infiltrated into the soil.

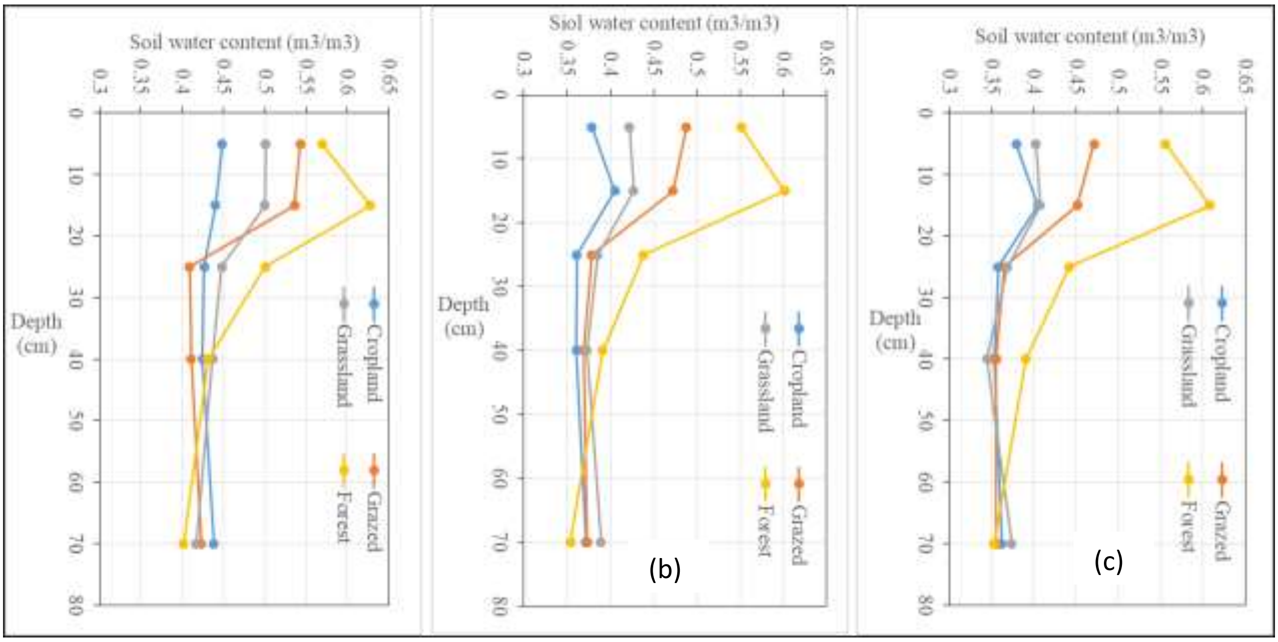

Figure 6.19: Seasonal patterns of the simulated vertical soil water variations for different land use/cover: (a) SON, (b)DJF and (c) MAM

Influence of farming on soil water content

The mean soil water was highest in the forest and lowest in the cropland in all seasons and at all depths except 65-70 cm. Thus the forest and cropland represented the extremes of soil water in the catchment. Comparison of these two extremes was done in order to determine depth and the season when soil water difference is greatest. Soil water content differences were computed by subtracting the soil water at a given layer in the forest with the corresponding value in cropland. The results showed that the MAM season had a difference in soil water of 0.204 m^3/m^3, between the forest and the cropland. While the DJF season had a difference in soil water of 0.196 m^3/m^3 and the lowest difference in soil water content occurred in SON season 0.187 m^3/m^3 in the 10-15 cm soil depth (Table 6.5). The differences in soil water between the seasons could be attributed to variability in the amount of rainfall among the seasons. For instance, the MAM season had a significantly more rainfall than the SON which could explain the significant differences in soil water. Similarly, the DJF season showed a significantly higher differences in soil water content between forest and the cropland than the SON season which was attributed to the more rainfall amount experienced in the DJF season during the study period (Table 6.6). The occurrence of higher soil water differences between forest and cropland was attributed to the direct exposure of the cropland to sun and wind which increase the rate evapotranspiration while the forest is shielded by the forest canopy. These results also showed that the differences in soil water content between the forest and the cropland was greater in times of high rainfall than in times of low rainfall. These results show that the upper layers 0-5 cm and 10-15 cm were more vulnerable to environmental changes than the lower layers.

Table 6.5: Variability of the mean soil water for different seasons in the land use/cover types considering the highest (Forest) and the lowest (Cropland) soil water contents respectively.

Soil depth (cm)	SON Mean soil water (m^3/m^3)			DJF Mean soil water (m^3/m^3)			MAM Mean soil water (m^3/m^3)		
	CL	FT	FT-CL	CL	FT	FT-CL	CL	FT	FT-CL
0-5	0.448	0.570	0.122	0.378	0.551	0.173	0.379	0.556	0.177
10-15	0.440	0.628	**0.188**	0.405	0.601	**0.196**	0.405	0.609	**0.204**
25-30	0.427	0.501	0.074	0.361	0.439	0.078	0.358	0.442	0.084
40-45	0.424	0.431	0.007	0.361	0.391	0.030	0.353	0.391	0.038
65-70	0.438	0.402	0.036	0.372	0.354	0.018	0.362	0.353	0.009

Note: CL = Cropland, FT =Forest

Table 6.6: The multi-comparison of rainfall in the seasons SON, DJF, and MAM

Seasons	**Seasons**	**Seasons**	**Mean difference (in rainfall mm/day)**	**P value**
SON		DJF	7.707*	0.001
		MAM	6.371*	0.007
DJF	SON		7.707*	0.001
	MAM		1.336	0.520
MAM	SON		6.371*	0.007
	DJF		1.336	0.520

Note: * Means all p-values are significant at p<0.05

6.3.4 Influence of land use/cover on surface runoff generation

After each rainfall event, within the period between October 2015 and June 2016, water generated as surface runoff was collected in each land use/cover. The volume of water collected was recorded in mm/day to be comparable to the rainfall. The cropland generated runoff faster than other land cover types. For instance, after rainfall on 01/20/2016, the cropland showed a runoff of 1.07

mm/day followed by grazed land (0.01 mm/day), while the wooded grassland and the forest did not show any runoff. After 5 days of rainfall, the runoff in the cropland increased to 1.97 mm/day while the grazed, wooded grassland and forest each had 0.18 mm/day, 0.03 and 0.03 respectively (Figure 6.20). These results imply that cropland responds faster to rainfall and produces higher surface runoff than the other land cover types. This was attributed to the fact that cropland is affected by raindrop impact that closes the pores of the soil preventing infiltration hence resulting to surface runoff. There were noteworthy differences in the runoff generated in the various land use/cover types following rainfall events. For instance, following the rainfall during the September and November (SON) 2015 season, the cropland recorded the highest runoff of 6.73 mm/day while the lowest was recorded in the forest (1.31mm/day) after rainfall of 15.4 mm/day on 05/12/2015. It was interesting to note that this highest runoff in the cropland (6.73 mm/day) was caused by a rainfall which fell after 3 days of no rainfall with a rainfall intensity of 13.6 mm/hour and a duration of 11 hours. While a higher rainfall of 35.6 mm/day on 29/10/2015 with a rainfall intensity of 34.4 mm/hour and a duration of 3.5 hours only caused a runoff of 2.24 mm/day. These observations show that the relationship between runoff and rainfall is not always linear. Thus implying that apart from the amount of rainfall, runoff generation is governed by other factors such as the antecedent soil water content, rainfall characteristics as well as land cover characteristics. Subsequently, during the drier season in January 2016, the runoff in the cropland was 3.22 mm /day while in the forest the runoff was only 0.41mm/day in a day when rainfall was 13 mm on 14/01/2016.

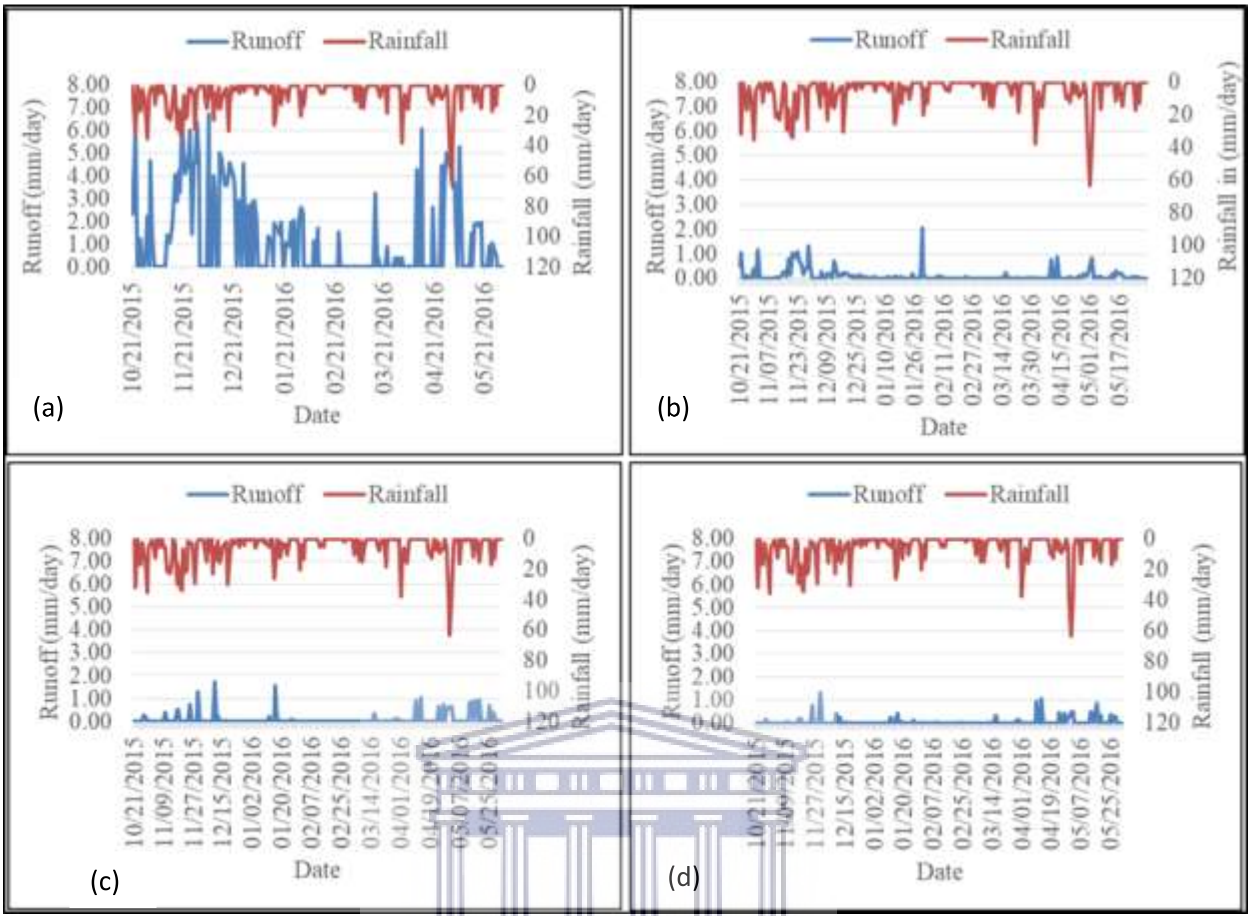

Figure 6.20: Temporal variation of daily rainfall and runoff in different land use/cover types (a) cropland (b) wooded grassland (c) grazed and (d) forest

The mean runoff in each land use/cover type was compared among each other. The results showed that cropland had the highest runoff with a mean of 7.63 mm/day followed by grazed, and wooded grassland. When pairs of means of runoff from different land use/cover types were compared, cropland produced significantly higher mean runoff than all others and the forest had lowest (Table 6.7). These results imply that the cropland in this catchment has the potential to lose more water as surface runoff than the other land use/cover types.

__Table 6.7: Comparison of mean runoff from different land use/cover types from October 2015-June 2016__

Factor	Land use/cover type (pair) for comparison	Mean runoff (u) (mm)		t-value	p-value
Mean runoff	CL&GZ	CLu= 7.63	GZu= 0.68	9.13*	0.000
	CL&WGS	CLu= 7.63	WGSu= 0.54	9.32*	0.000
	CL&FT	CLu= 7.63	FTu= 0.34	9.63*	0.000
	GZ&WGS	GZu= 0.68	WGSu= 0.54	2.68	0.341
	GZ&FT	GZu= 0.68	FTu= 0.34	9.51*	0.008

__ means the mean runoff is significant at p<0.05, CL=cropland, GZ=grazed, WGS= wooded grassland, FT=forest__*

The diverse rainfall events in the catchment resulted in different runoff coefficients among the land use/cover types. The runoff coefficients (RC) were low in all the land use/cover types. For instance, the mean RC was lower than 2% for most rainfall events in the forest, grazed and wooded grasslands and only the cropland had a mean RC of 0.26 (26%). The RC resulting from the cropland was 26 times that of the forest and wooded grasslands and 13 times that of the grazed land (Table 6.8). These results show that much of the rainfall infiltrates into the soil in the forest, grazed and wooded grasslands while 26% of the rainfall becomes runoff in the cropland. Only 2% of rainfall becomes runoff in the grazed land. The reason for the low RC values in the forest, grazed and the wooded grasslands is due to the abstraction of rainfall by vegetation in the forest and storage of water in the soil for the forest and grasslands that promotes infiltration.

Table 6.8: Mean runoff coefficients in different land use/cover types

Land use/cover	RC (runoff/rainfall)
CL	0.26
GZ	0.02
WGS	0.01
FT	0.01

Note: RC=Runoff Coefficient, CL = cropland, GZ= grazed land, WGS = wooded grassland, and FT = forest land. RC in CL = means of runoff coefficient in the cropland etc.

6.3.5 Relationship between generated runoff and rainfall characteristics in different land use/ cover types

In order to understand the influence of rainfall on surface runoff generation in different land use/covers, various rainfall characteristics (including daily rainfall, rainfall intensity and rainfall duration) were correlated with the daily runoff from each land use/cover type for the period from October 2015 to June 2016. The daily rainfall significantly correlated with the runoff from all the land use/cover types except the forest (Table 6.9). However, there were no significant correlations between each of the other rainfall characteristics (i.e. rainfall intensity and rainfall duration) and runoff in all land use/cover types (results not shown).

Table 6.9: Correlation between rainfall and runoff for different land use/cover types for the study period October 2015-June 2016

Land use/cover type	Rainfall-Runoff correlation	
	R^2-value	p-value
CL	0.387*	0.000
GZ	0.305*	0.000
WGS	0.147*	0.028
FT	0.082	0.220

Note: all the p-values are significant at $p<0.05$, CL=cropland, GZ=grazed, WGS= wooded grassland, FT=forest;

6.4 Discussion

The influence of land use intensification and land use/cover changes on soil properties and the effect of these changes on the soil water content and runoff generation were examined. From the field study using small plots, spatial variations of soil properties were detected and consequently soil water content variations that could not have been detected if the soils were studied at catchment scale (Githui et. al., 2009; Mango et. al., 2011). However, since the experimental plots were spread out in the whole catchment in each land use/cover, these results were representative of the catchment. The observations from these experiments were therefore averaged and used to inform the variations of each component in each land use/cover in the catchment. In general, there was significant alteration of soil properties with reduced soil organic carbon (SOC) and increased bulk density (BD) within the croplands compared to the other land use/covers. Field measurements of soil water and simulation using the Hydrus-1D model revealed significant differences in soil water content among the different land use/cover types and at various depths. These results indicate that subsistence farming activities have altered the SOC and BD in the catchment that are potentially altering the soil water retention. Similar results were observed by Kavian et. al. (2014) in Northern Iran who indicated that changes from natural forest to cultivation reduces the SOC and increases the BD of the soil. The soil infiltration rates have also altered soil water in different land use/cover types. For instance, the high soil water content observed in the forest land was attributed to the high hydraulic conductivity and porosity as well as the observed high infiltration rate. Alaoui et. al. (2011) also found that the forest soil structure was characterised with high hydraulic conductivity improved the infiltrability of soils and consequently increased soil water in Kandergrund, Bern, (Switzerland).

The altered soil properties have consequently affected the variability of soil water content in different land use/cover types as well as in different depths of the same land use/cover. At shallow depths 0-30 cm both croplands and grazed lands showed significantly low soil water contents than forest land. The higher soil water content in the forest land was attributed to low evaporation from the floor of the forest because of the litter and also shading by the canopy that reduces solar radiation received and prevents evaporation as was also reported by Kavian et. al. (2014). Higher soil water content in the forest at shallow depth could also have been as a result of the promotion of meso-pores allow the forest to hold more water as opposed to wooded grasslands that have macro-pores that allow transmission of water into the deep soils rather than store it (Yu et. al., 2015). This was clearly observed in this study where the forest land was found to retain more water than the other land use/cover types in the layer between 0-30cm. Yu et. al. (2015) reported similar findings in the Loess Plateau in China where grasslands allowed passage of more water into the soil than the forest. Overturning of the top soil during cultivation and grazing was associated with high BD and low SOC that reduce infiltration capacities of the soil which was attributed to the low soil water content in these land use/covers. Similar observations were made by Yimer et. al. (2008) in Ethiopia who found that large bulk densities in the soils lowered the soil water contents. There was a marked lack of differences among the land use/cover types in soil water content at depths beyond 30 cm. This indicated that compaction of soils by farm machinery and trampling by animals in the cultivated and grazing lands respectively have mainly affected soil water content in the upper layers of these soils. Similar results were found by Toro-Guerrero et. al. (2018) in Mexico who noted that upper layers of soil experienced more variability of soil water than deeper layers across seasons and in each land use/cover.

The vertical soil water content in each land use/cover type was dependent on rainfall variability; being high during the wet period and low during the dry period. However, the highest values in each period were recorded in the forest while the lowest were in croplands. The highest difference in soil water content in any season was between the forest (high) and cropland (low) at the 10-15 cm depth. This difference was attributed to the higher evaporation from the cropland and the conservation of moisture by the mulching and minimal evaporation in the forest. Guo et. al. (2020) noted that the upper layer is an active interface between the atmosphere and the soil. The upper layer is also more influenced by precipitation and evaporation and therefore more soil variability exists. These results are in agreement with those of Famiglietti et. al. (1998) who found that higher mean soil water content in a catchment is often associated with higher variability.

The surface runoff collected in each land use/cover type after rainfall showed that the cropland responded faster to rainfall than the other land covers while the forest exhibited considerable delay. This was attributed to the exposure of cropland to rain beating therefore sealing of the soil pores that lead to faster generation of runoff. This was also evidenced by the significant relationship between rainfall and runoff where the cropland portrayed the highest correlation while the forest had no correlation. The effects of the changes in land use/cover was also demonstrated by the significantly higher runoff coefficient (RC) 26 % in the cropland as compared to either the wooded grass (1%) or the forest (1%) lands (the initial land cover types before land use/cover conversion). These results imply that more rainfall is usually converted to runoff by the cropland compared to forest and grasslands. The reason for the higher runoff experienced in the cropland is due to the increased bulk density that was observed in this land cover that impedes infiltration hence more surface runoff. Girmay et. al. (2009) in a cultivated land in Tigray, (Northern Ethiopia) observed similar range of RC values (0.23-0.39) while Recha et. al. (2012) in an agricultural land that had been cultivated for over 50 years in a sub-humid region of Western Kenya found RC value of 0.32.

The results in this chapter together with the results on ET (Chapter 5) indicate that the increased cropland at the expense of the forest cover (observed in Chapter 3) together with land use intensification (Chapter 4) have considerably altered the way rainfall is partitioned in this catchment. Consequently, more surface runoff is generated at the expense of soil water in the catchment while less water is lost through ET (Chapter 5). The net effect of these changes were observed in the characteristics of the Nyangores River streamflow that is investigated in the next chapter.

6.5 Summary

The aim of this Chapter was to establish how changes in land use/cover (particularly subsistence farming) could be affecting rainfall partitioning in terms of soil water and runoff generation in Nyangores River Catchment. This chapter is building on the previous chapter on water lost in the catchment through ET (Chapter 5). In this chapter, experimental plots that were representative of the catchment were used to generate, soil properties/water and surface runoff data. Such primary data taken at fine spatial scale are important in validation of various hydrological models and are lacking in most hydrological studies done in the data scarce African region. Using these data, it was established that changes in land use/cover together with land use intensification have significantly altered the soil properties, soil water retention, and consequently surface runoff generation in the catchment. For example, forest achieved higher soil water faster than other land cover types and maintained more soil water over a longer period. The vertical soil water variability across the land use/cover types revealed that the 0-15 cm soil depth had the highest differences in soil water mainly between the forest and the cropland. Furthermore, the forest had almost negligible surface runoff and least alteration of the soil properties. These results imply that the undisturbed land had the least adverse effect on the soil water of the catchment although on the other hand the forest exhibited the highest ET rate (Chapter 5). The implications of the altered hydrological processes in the catchment are likely to influence the river flow characteristics of the Nyangores River. The long-term streamflow characteristics of this river were investigated in the next chapter (Chapter 7).

CHAPTER 7: DETECTION OF CHANGES OF LONG-TERM STREAMFLOWS OF NYANGORES RIVER

7.1 Introduction

From the preceding chapters, the Nyangores River Catchment has undergone significant land use/cover changes (Chapter 3&4) that has consequently altered the way rainfall is partitioned into ET, soil water and runoff (Chapters 5&6). The net effect of these change on the hydrology of the catchment is likely to be felt in the river. The objective of this chapter was to investigate if the altered hydrological processes by human activities have altered the streamflow characteristics of the Nyangores River by examining the long-term changes of the key indicators of hydrological alterations. Therefore, this chapter sought to establish whether the land use/cover changes and the subsequent changes in rainfall partitioning that were observed within the catchment (using field survey, remote sensing and experimental plots) have impacted on the river flow characteristics. It is important to note that the decade between 1979 and 1989 was observed to be the period when population (and households) increased markedly and hence the time when major changes in land use/cover took place within this catchment (Chapter 3). Thus, it was the period when the river was expected to experience significant change. In this Chapter, it was hypothesized that substantial alterations of the land use/cover and the subsequent continuous cultivation and grazing activities have altered the streamflow characteristics of the Nyangores River particularly after 1989.

7.1.1 Factors influencing streamflow in a catchment

Streamflow provides key ecological services to the river ecosystems such as flood plains and alluvial aquifer (Poff et. al., 2010; Ekka et. al., 2020). Streamflow is also important in controlling and maintaining the function, structure and dynamics of the river ecosystems in riparian zones including the neighbouring wetlands (Anandhi et. al., 2018). The streamflow characteristics such as high and low flows in relation to their magnitude, timing and duration are important in the provision of the expected conditions for the maintenance of the river ecosystems (Richter et. al., 1998; Kabite, 2018; Gebremicael et. al., 2019; Grantham et. al., 2019; Yaseen et. al., 2022). Human activities influence river flow characteristics (particularly the base flow) mainly through indirect mechanisms associated with changes in land use/cover and to some extent through direct water abstraction and impoundments of water in streams, (Gao et. al., 2011; Mwangi et. al., 2016; Sungu, 2018; Omonge et. al., 2020).

Changes in catchment hydrology normally hinder provision of services to the river ecosystems by streamflow. Land use/cover changes and land use intensification of the magnitude observed in Chapter 3&4 of this thesis have the potential to alter the magnitude, timing, duration of high and low flows including the base flow. The effects of land use/cover on the rainfall partitioning in the catchment was established in this thesis. For instance, the amount of water lost through ET was found to have been affected by the conversion of forest cover to other land use/cover types; particularly the change of forest to bare and built up land which significantly decreased the water lost through ET. Also the conversion of forest to cropland means that the water lost by the crops would vary according to the growing season (high when crops are mature and low during initial stages) while the water lost by forest is almost invariable throughout the year (Chapter 5). From Chapter 6, the soil water was established to have been altered due to changes in land use/cover; the catchment was losing more water in the cropland as surface runoff and retaining less than the wooded grassland and the forest. These alterations of the hydrological processes within the catchment are likely to be manifested as changes in the streamflow characteristics (Fentaw et. al., 2017).

Apart from the influence of human activities, climate change/variability could influence changes in streamflow characteristics. In particular, increasing temperatures and varying precipitation regimes (Gachahi 2016; Dey & Mishra, 2017; Philip et. al., 2022) can cause significant impacts on hydrological processes in a catchment. Studies indicate that increased/decreased long-term rainfall regimes increases/decreases streamflow while increasing/decreasing temperatures may increase/decrease the rate of evaporation (Legesse et. al. 2003; Guo & Hu 2008; Zhang et. al. 2019; Philip et. al., 2022). These studies illustrate the need to include the influence of climate change/ variability when attributing changes in long-term streamflow characteristics in a catchment.

The methods used to investigate the effects of human and/ or climatic factors on streamflow are varied. Some use hydrological models (Nobert & Jeremiah, 2012; Baker & miller, 2013; Piras et. al., 2014) while others use parametric and non-parametric statistical methods to detect changes in the various river flow variables (Kashaigili & Majaliwa, 2013; Ahmad et. al., 2015; Mwangi et. al., 2016; Fentaw et. al., 2017; Yaseen et. al., 2020). Some studies focus on single index such as peak flow (Wang & Melesse, 2006) and minimum flows (Smakhtin, 2001; Stéphane & Renaud, 2009; Price et. al., 2011). However, studies have recommended the use of multiple variables of streamflow characteristics in order to understand the multiple-impacts of hydrological changes in river catchments (Mathews & Richter, 2007; Yang et. al., 2008; Gao et. al., 2009; Belihu et. al., 2020). In order to extract multiple variables of the streamflow that can be used to evaluate the influence of multi-impacts of hydrological changes, Taylor et. al. (2003) recommends the use of Indicators of Hydrologic Alteration (IHA) software that is developed and distributed by US Nature Conservancy (Richter et. al., 1996; 1997).

7.2 Methodology

7.2.1 Data sources

In order to establish the hydrological changes in the catchment, the streamflow characteristics of the Nyangores River were investigated using daily river discharge data for the period between 1965 to 2016 obtained from the Water Resources Management Authority (WRMA). The river gauging station (ILA03) is located at the exit of the catchment at Bomet Town (refer to Figure 2.1 in Chapter 2). Climate change was investigated using the daily temperature and rainfall (from three rainfall stations within the catchment) obtained from the Kenya Meteorological Department (KMD). The climate data were used to investigate whether there have been temporal trends in rainfall and/or temperature in the catchment which could influence the characteristics of the Nyangores River flow. Note that complete time series of temperature data was available from 1986 to 2016 while rainfall data length varied according to the station (Table 7.1).

Table 7.1: Temperature, rainfall, and river discharge data for analyzing the streamflow characteristics

Name of station	Station code	Type of data	Period	Number of years
Kericho Weather Station	9035279	Temperature	1986-2016	30
Nyangores Forest Station	9035302	Rainfall	1980-2014	34
Bomet Water Supply	9035265	Rainfall	1967-2008	41
Kiptunga Forest Station - Elburgon	9035228	Rainfall	1961-2008	47
Bomet RGS	(ILA03)	River discharge	1965-2016	51

7.2.2 Data analysis

Data quality control

Prior to data analysis the daily temperature, rainfall and streamflow data were checked for quality and tested for normality using Kolmogorov-Smirnov statistic (Zaiontz, 2015). The seasons used for rainfall and temperature analysis are December-February (DJF) representing the dry season, March-

May (MAM) locally called the long rain season, June-August (JJA) representing the cool monsoon season and September-November (SON) representing short rain season.

Statistical analysis

The trend analysis was performed using the Mann-Kendall (MK) trend test (Kendall, 1975) which is appropriate for time series without seasonal or cyclic behaviour (Biggs & Atkinson, 2011). This method has the advantage that it is a non-parametric test that does not require the data to be normally distributed and the results are not affected by outliers or missing values (Lanzante, 1996; Asfaw et. al., 2018; Yaseen et. al., 2022). Mann-Kendall test due to its robustness has been used in detecting trends in hydrologic and climatologic time series. Although no assumption of normality is required, the data should have no serial correlations for the p-values to be correct. The test is monotonic therefore does not change due to power transformation (Helsel & Frans, 2006). An elaborate description of Mann Kendall can be obtained from Gachahi (2016), and Fentaw (2017).

Indicators of hydrologic alteration

The daily river discharge data were further used to obtain flow indices that were used to analyse the characteristics of the streamflow. The indices were obtained using the Indicators of Hydrologic Alteration (IHA) software (Table 7.2). Many studies have used data from the IHA software to understand hydrological alterations in river flows after changes of land use/cover in catchments (Mathews & Richter, 2007; Yang et. al., 2008; Fentaw et. al., 2017; Gebremicael et. al., 2019; Belihu et. al., 2020). For instance Taylor et. al. (2003) used flow indices derived from IHA software to assess the extent of alteration caused by human induced changes to the hydrological regime on Mkomazi River, KwaZulu-Natal, (South Africa). The various flow indices selected for this study were the extreme flow magnitudes whose alterations would be critical in water resource management (either in floods for high magnitudes or water scarcity during low flows).

Table 7.2: Flow indices from the IHA software and their descriptions

Flow indices	Description of indices
Monthly mean flows	Mean value for each calendar month ($m^3\ s^{-1}$)
1, 3, 7, 30 and 90-Day minimum flows	Annual 1, 3, 7, 30, and 90-day minimum flow mean ($m^3\ s^{-1}$)
1, 3, 7, 30 and 90-Day maximum flows	Annual 1, 3, 7, 30, and 90-day maximum flow mean ($m^3\ s^{-1}$)
Base flow index	7-day minimum flow divided by mean daily flow for each year ("base flow") (dimensionless)

7.3 Results

7.3.1 Normality test

From the normality test the stream flow, rainfall and temperature data did not have a normal distribution. There were no serial correlations in the stream flow, rainfall and temperature data. Therefore, trend analysis of the data was done using the Mann-Kendall non-parametric method.

7.3.2 Analysis of temperature

The mean annual maximum temperature in the catchment for the period 1986-2016 ranges between 23.1^{0}C and 25.1^{0}C while the mean annual minimum temperature for the same period were between 10.7^{0}C and 12.0^{0}C. However, the temporal variability of mean annual maximum and minimum temperature shows an increasing trend (Figure 7.1). Therefore, further analysis to examine if the trends were statistically significant was done at various time scales.

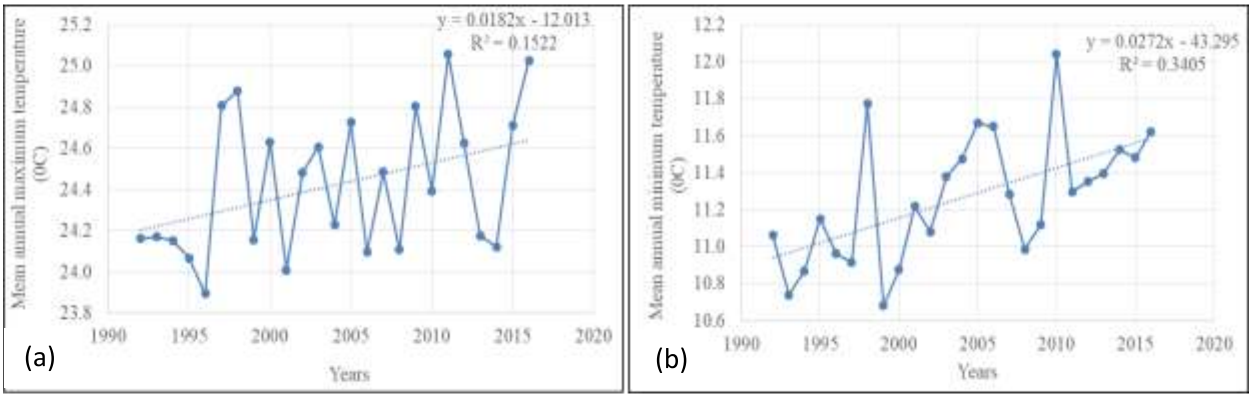

Figure 7.1: Temporal variability of the mean annual (a) maximum and (b) minimum temperatures of Nyangores River Catchment at Kericho Weather Station.

The results of the trend analysis of temperatures showed that, the mean annual minimum temperature had a significant increasing trend. The seasonal minimum temperatures for MAM, JJA and SON also had significant increasing trends. The maximum temperatures had increasing trends only for the month of June and July and consequently the JJA season (Table 7.3). In summary, it was noted that the minimum temperatures which occur mostly at night had increasing temperature in a catchment would imply an increase in evaporation (since evaporation is a function of temperature) and could influence the river flow characteristics. Noted however was that the increasing temperatures in this catchment were during the cold (JJA) season.

Table 7.3: Trends for the mean monthly, seasonal and mean annual T_{min} and T_{max} from 1986-2016. All values shown are significant ($p<0.05$); the positive τ values indicate an increasing trend.

Temperature ^{0}C	**Kendall Tau (τ)**	**P-value**
T_{Min}May	0.320	0.028
T_{Min}Sep	0.307	0.036
T_{Min} mean annual	0.450	0.000
T_{Min}MAM	0.375	0.010
T_{Min}JJA	0.299	0.041
T_{Min}SON	0.392	0.008
T_{Max}June	0.358	0.014
T_{Max}July	0.478	0.001
T_{Max}JJA	0.459	0.002

T_{Min}/T_{Max} signifies minimum/maximum temperature respectively

7.3.3 Analysis of rainfall

The pattern of temporal variability of rainfall in Nyangores River Catchment signifies high inter-annual variability for the annual and season totals for the period between 1961 and 2008. The highest annual rainfall was 1600 mm/year and lowest was 1000 mm/year and in many years the rainfall was above the mean annual (1340 mm/year). The periods of high/low rainfall could be associated with periods of high/low peak discharge of the streamflow. Likewise, the seasonal rainfall variability showed that in some years the MAM seasonal rainfall was as high as 600 mm but it could go as low as 200 mm with a mean of 450 mm. For the OND the highest mean annual rainfall was 500 mm and the lowest was 150mm. In both the annual and the seasonal time series of rainfall there were no observable trends (Figure 7.2).

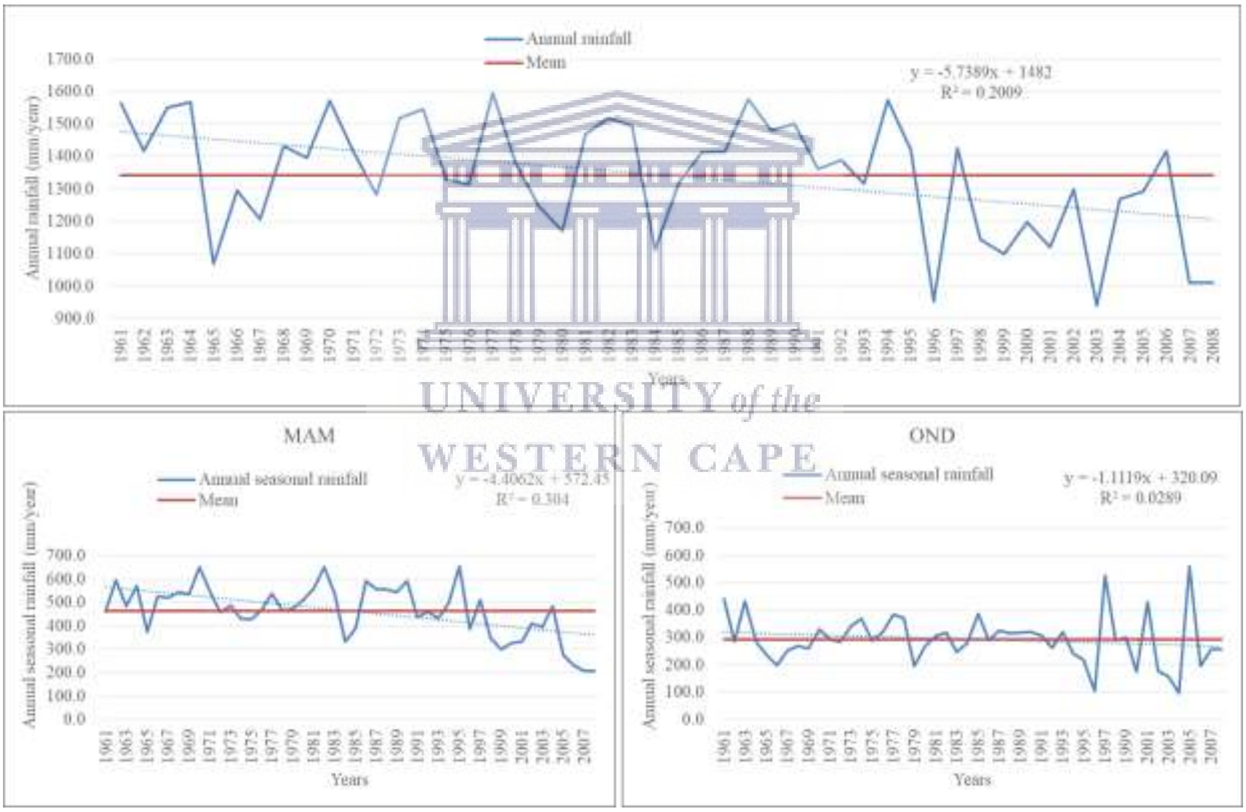

Figure 7.2: Temporal variability of annual rainfall for Kiptunga Forest Station (1961 to 2008) in Nyangores River Catchment; Long-term annual rainfall mm/year, MAM seasonal rainfall and, OND seasonal rainfall

7.3.4 Analysis of the streamflow

The temporal variability of the mean annual streamflow indicated periods of high and low flows and a noticeable increasing trend (Figure 7.3). Various variables of the streamflow characteristics including mean annual, seasonal and monthly flows were tested for temporal trends using Mann-

Kendall trend analysis method. The mean annual flow showed a significant increasing trend. Similarly, the total monthly flows of January, February, October, November, December, and the SON and DJF seasons had significant increasing trends at 5% level of significance ($p<0.05$) (Table 7.4). These results showed that the increasing total monthly flows were mainly for the dry season months. These results indicate that the low flows of the Nyangores River have increased over time even when rampant land use/cover changes have occurred.

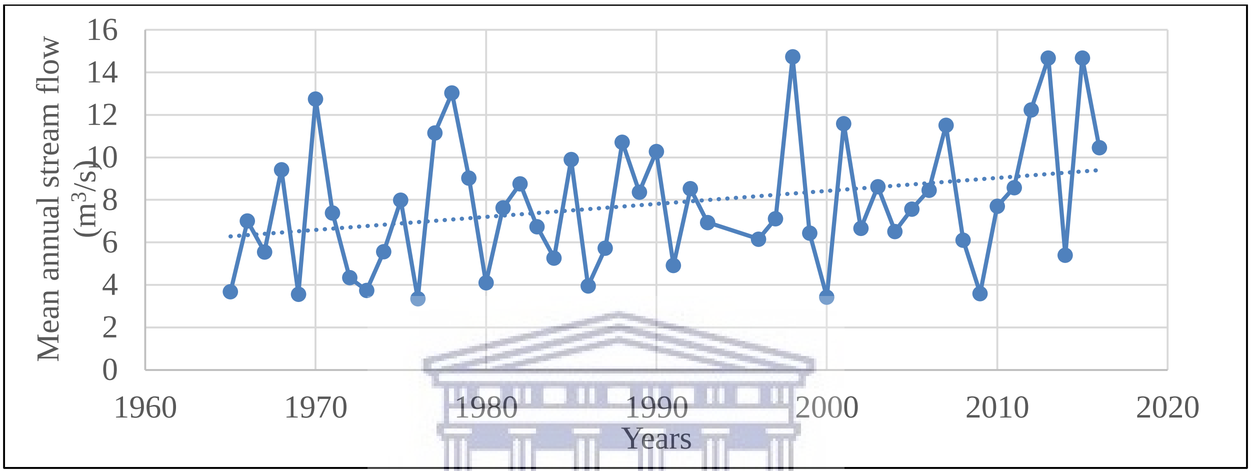

Figure 7.3: Temporal variability of the mean annual streamflow for Nyangores River at Bomet RGS (ILA03).

Table 7.4: Trends of the Nyangores streamflow at Bomet RGS (ILA03) (1965-2016)

Streamflow discharge (m^3/s)	**Kendall Tau (τ)**	**p-value**
January	0.304	0.002
February	0.214	0.030
October	0.207	0.035
November	0.287	0.004
December	0.197	0.046
DJF season	0.277	0.005
SON season	0.208	0.033
Mean annual	0.197	0.044

Note all the Kendall Tau (τ) values are significant at α=0.05

7.3.5 Temporal variability of the flow indices

The exploratory analysis of IHA, showed that the minimum flows and the base flow index were increasing with time during the period between 1965 and 2016 while maximum flows had no observable change (Figure 7.4). Generally, all these minimum flow indices appear to have started to increase gradually from 1990; for instance, beyond 1990 most of the flows of the 1-day minimum were above the mean of 0.79 m^3/s. The same increasing pattern was observed for the base flow. It is worth noting that 1979-1989 was the period over which the catchment experienced remarkable changes in population and land use/cover (Chapter 3).

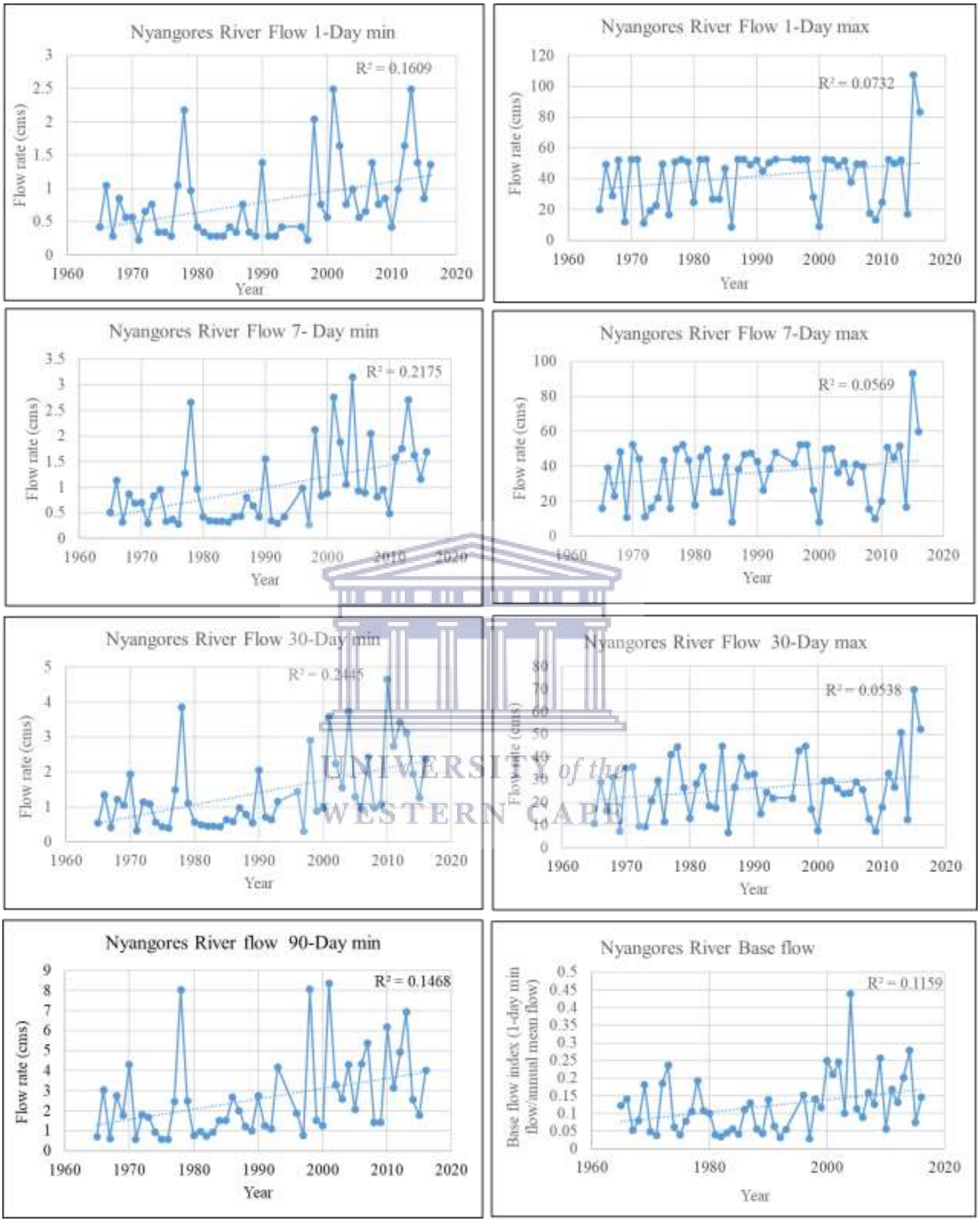

Figure 7.4: Illustrations of temporal variability of the annual flows and the base flow index for Nyangores River at Bomet RGS (ILA03) 1965-2016.

On testing the trends, the minimum flow indices and the base flow index were significantly increasing (at the 5% level of significance) (Table 7.5). The increasing minimum flows experienced in the catchment signifies changes in the hydrological behaviour of the catchment particularly during the dry season. The results suggest that land use/cover changes observed in the catchment are the major course of the observed changes in the minimum and the base flows although changes in the climatic factors could also play part.

Table 7.5: Trends of the flow indices of the Nyangores River from 1965 to 2016

Flow indices	Kendall Tau (τ)	p-value
1-Day minimum	0.258	0.012
3-Day minimum	0.286	0.005
7-Day minimum	0.305	0.002
30-Day minimum	0.343	0.001
90-Day minimum	0.324	0.001
Base flow index	0.243	0.015

Note: all the Kendall Tau (τ) values are significant at α=0.05; Trends that were not significant were not shown.

7.3.6 Streamflow changes before and after major changes in the catchment

Human population increased remarkably in the study area during the period between 1979 to 1989 (Chapter 3). Consequently, substantial land use/cover changes occurred during this decade. The time before 1989 was therefore considered in this study as the period before major changes occurred and referred to as *pre-impact* while the time after 1989 was the period after major changes occurred and was referred to as *post-impact*. The streamflow data were therefore divided into two parts for the statistical analysis of any significant changes in the river flow characteristics. The discharge data for 1965 to 1989 (24 years) represented the *pre-impact* period while 1990 to 2016 (26 years) represented the *post-impact* period. For each period shifts in the 25th, 50th, and 75th percentiles of the flow indices including the base flow were examined. The results indicated that there were significant shifts of the 25th, the median and the 75th percentile of the minimum flows. For example, the 75th percentile of the 3-day minimum flow had a significant upward shift from a *pre-impact* value of 0.8 m^3/s, to a *post-impact* value of 1.8 m^3/s. The base-flow index, also had a upward significant shift during the *post-impact* period (Figure 7.5). For the maximum flows, there were no signicant shifts in any of the percentile (results not shown).

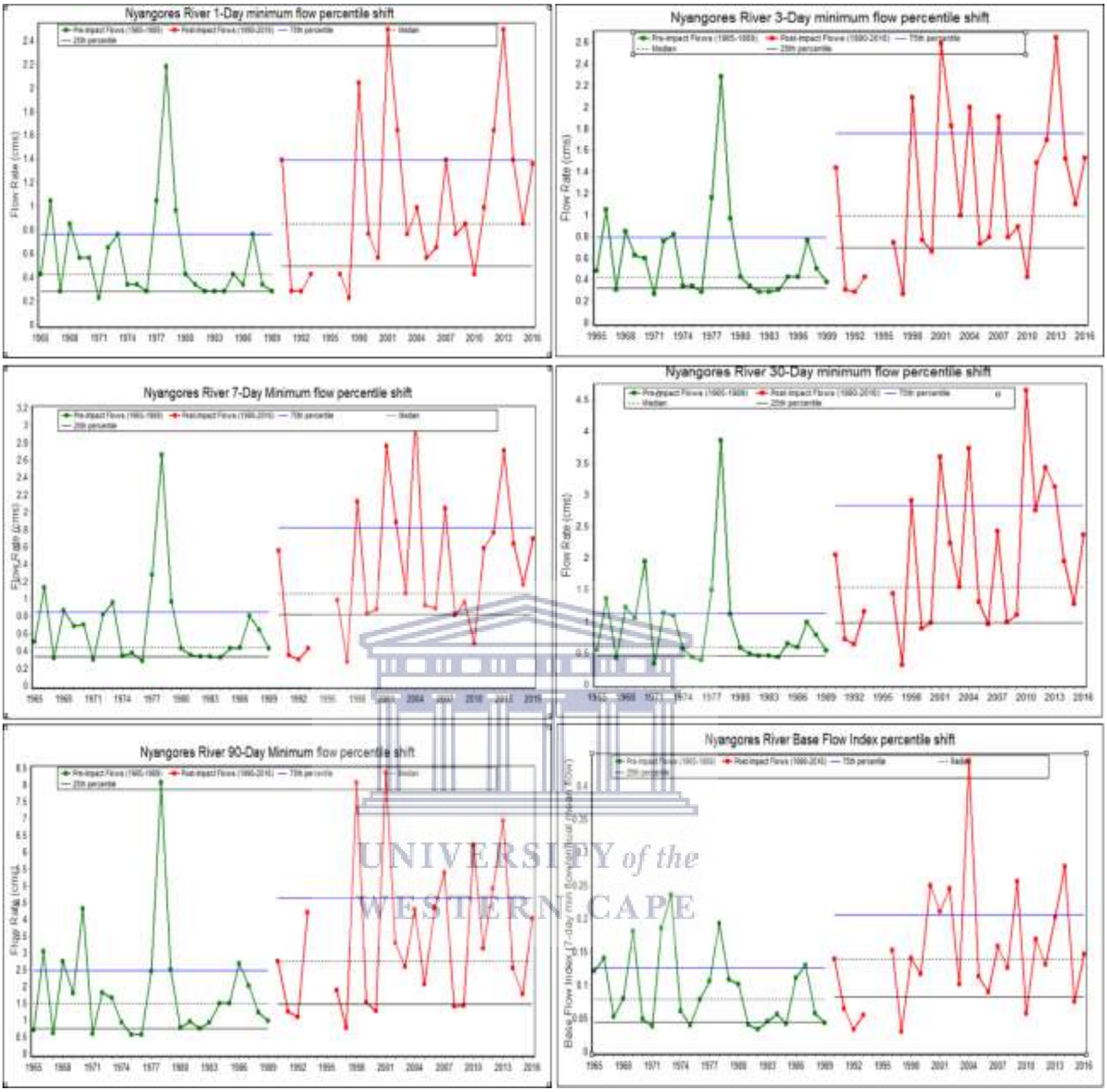

Figure 7.5: Percentile shifts between pre and post impact periods for the; 1-day, 3-day, 7-day, 30-day, and 90-day minimum flows and the Base flow index for Nyangores River at Bomet RGS (ILA 03).

7.3.7 Statistical relationship between the streamflow and climatic factors

In order to examine if the observed increasing trends in the streamflow characteristics could be attributed to rainfall and temperature (climatic factors), correlation coefficients were computed. There were no significant correlations between rainfall and the river flow indices (at the 5% significant level). Furthermore, even the increasing minimum and maximum temperature were not significantly correlated with any of the changing streamflow variables. This implies that the observed river flow changes are most likely as a result of changes in the land use/cover.

7.4 Discussion

The Nyangores River has a catchment with a sub-humid climate which receives rainfall almost throughout the year with two seasonal peaks (MAM and SON). This river catchment has undergone significant land use/cover changes for the last thirty-six years with most of the natural forest converted to farmlands (croplands and grazed lands) (Chapter 3). The continuous conversion of natural forest to croplands and later the intensified use of land (Chapter 4), has consequently altered the way rainfall is partitioned in the catchment. There was reduced ET due to loss of forest cover, reduced soil water and increased runoff within the cultivated lands due land use intensification (Chapter 5& 6). These changes, were expected to influence changes in the streamflow characteristics such as the maximum and minimum flows. Therefore, the streamflow characteristics including total monthly flow together with several flow indices that are indicators of hydrological alterations were investigated for temporal trends and percentile shifts. The results showed significant increasing trends of the river discharge particularly during the dry season (DJF). Moreover, the indices of minimum flows and the base flow index also showed significant increase for the period between 1965 and 2016.

Further when the discharge data was divided into periods before and after respectively major land use/cover changes were realized in the catchment (referred to as *pre-and post-impact* periods), the 25th, 50th and 75th percentiles of the minimum flows and the base flow of the post-impact period were significantly higher than for the pre-impact periods. These results indicate that the catchment is responding to the changes over time in land use/cover. The increase in the base flow during the *post- impact* period suggest that water is coming from the sub-surface to sustain the river flow during the dry seasons. The increased water was attributed to the reduced ET (observed in Chapter 5) due to decreased forest cover in the catchment. Note that reduced forest cover reduces the amount of soil water taken up through capillarity by the deep roots of the trees which is then lost through evapotranspiration. The loss of 55% forest cover within a period of thirty-six years to mainly crop and wooded grasslands (Chapter 3) is likely to have resulted in improved retention of water in the catchment hence increasing the subsurface flow into the river. Dias et. al. (2015) in a study in the Upper Xingu River Basin, Central Brazil also found increased streamflow that was attributed to decreased evapotranspiration following conversion of forest to agricultural land.

The degraded forest cover in Nyangores River Catchment have regenerated over time into wooded grasslands during the post-impact period particularly after forest encroachment was abolished and unlawful use of forest materials continued (Chapter 3). Studies indicate that wooded grassland loose less water through evapotranspiration than forest. For instance, Li (2017) established that conversion of forest to grasslands resulted into a reduction in ET in China. The difference in soil properties between the forest and wooded grassland could also explain why minimum flows have increased; forests promotes meso-pores due to the frequent wetting and drying that reduces the soil pores allowing them to hold more water that is later used for ET while the grasslands create stable macro-pores that allow percolation of water hence increasing sub-surface flow as indicated by Schwärzel et. al (2011) and Yu et. al. (2015). Similar results were also reported by Zhang & Wei (2012) in British Columbia (Canada) and Worku et. al. (2014) in Omo–Ghibe Basin in Ethiopia who observed increasing dry seasons flows and attributed it to a reduction in the water lost through ET when forest is reduced.

Streamflow characteristics could also be influenced by climatic factors such as rainfall and temperature. In this study however, rainfall had no significant change over the study period and hence had no significant influence on the changes in the streamflow characteristics. Similar observations were made by Gachahi (2016) who stated that annual and seasonal rainfall in Western Kenya did not have significant trends over the last fifty years. Similarly, the increasing trends in temperature (particularly minimum) in the catchment were also not significantly correlated with the increasing minimum flows. The lack of significant influence of the changes in river flow characteristics by the climatic factors validates that the observed changes in streamflow characteristics were as a result of land use/cover changes in the catchment.

7.5 Summary

The aim of this chapter was to investigate if land use/cover changes that have consequently altered rainfall partitioning in the Nyangores River Catchment have influenced the long-term streamflow characteristics of the Nyangores River. The Nyangores River passes through a sub-humid catchment that has rainfall almost throughout the year (with two seasonal peaks) and subsistence agricultural activities. The analysis of long-term streamflow data revealed significant increase in the minimum flows (dry season) over the last 51 years (1965-2016) while the maximum (wet season) flows had no significant change over the same period. One notable outcome of the analysis is that the dry season flows of the Nyangores River have particularly increased during the period when extensive land use/cover change occurred. This was attributed to the reduced ET as the forest cover reduced. Note that agricultural land does not take up as much water from the soil as the trees during the dry periods hence ET from cropland, grazed and wooded grasslands is less than that of the trees. Consequently, there is more water stored in the sub-surface to replenish the river during dry periods. Further, when clearing of forest was prohibited by the Kenyan government, available croplands were put under intensified agriculture (Chapter 4). This intensification was observed to result into high runoff and reduced soil water from croplands (observed in Chapter 6). However, the surface runoff does not seem to have significantly affected the maximum flows of the river. This was partly attributed to the presence of wooded riparian land in the catchment that prevent the surface runoff to directly reach the river but instead infiltrate into the soil thus the increased base flow. Although the rampant change in land use/cover and the subsequent land use intensification in the catchment have increased the dry season flows, studies have shown that when compaction from croplands exceeds the benefits of reduced ET, decreased low flows may be experienced in future. Furthermore, changes in soil properties that influence higher runoff in cultivated lands may reach a threshold that may cause reduction of the dry season flows.

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

8.1 Introduction

The aim of the work presented in this thesis was to contribute to knowledge on the influence of rampant land use/cover changes on the hydrological processes of a catchment. This research was motivated by the need to provide knowledge on the extent to which land use/cover changes influence rainfall partitioning and the possibility that these changes alter the streamflow characteristics. This study was carried out in the Nyangores River Catchment which lies in a sub-humid equatorial region in south-western Kenya. To achieve the aim of the study, seven chapters were formulated with all the necessary information needed to answer the research questions. The outcomes and major conclusions from these chapters are presented in the sections below.

8.2 Main findings of the study

8.2.1 Land use/cover changes and population dynamics.

The forest cover in Nyangores River Catchment was found to have reduced by about 55% over a period of about 36 years (1979-2016). Much of the forest was converted to croplands especially in the decade between 1979-1989 when human population increased rapidly due to migration and natural birth. A high proportion of the population in the catchment was found to be in the economically active age group (15-64 years) that interact more with the catchment through agricultural activities and use of the forest materials. The satellite images of 2010 and 2015 showed an increase in the wooded grassland at the expense of forest land that was attributed to clearing of trees in deep forests due to charcoal burning and logging after changes in government policies on forest protection in 2010 were enforced (Chapter 3). According to the communities, the destruction of forest resources was attributed to laxity in the law enforcement by the government officers and lack of adequate resources to protect the forest.

8.2.2 Nature of land use intensification within the catchment and factors driving it.

The increased population within the catchment, and prohibition of extension of cropland into the forest resulted into land use intensification. More than 95% of the farms were under semi-permanent and permanent cultivation and only about 5% of the farms were under shifting cultivation. The semi-and permanent land use practice is an indication of high land use intensity in which almost no substantial fallow period is allowed. The high land use intensity was attributed to the need to produce more food for the increased number of households in limited land area especially after extension of land into the forest was abolished by the government (Chapter 3). Apart from continuous cultivation of land, technological input such as fertilizer and mechanization that are regarded as significant stages in land use intensification have been adopted in the catchment. Land use intensification has adverse effect of on the hydrological processes mainly in influencing soil water movement in a catchment. Continuous overturning and compacting of soil influence infiltration and surface runoff generation.

8.2.3 Effect of changes of land use/cover on catchment hydrology.

The components of water balance in the catchment including ET, soil properties/water and surface runoff generation in the catchment were investigated.

Evapotranspiration

The spatial variation of actual evapotranspiration (ET_a) in the catchment was established through examining the surface energy balance elements in the different land cover types. The resultant of the variations of these energy balance elements was significantly higher ET_a rate in the forest than the other land cover types. The crop factors (K_c) of the most common vegetation types in the catchment were characterized. The average K_c values of forest and tea were lower than the standard values except during the wet period when the values were equal or slightly more. This was attributed to the fact that the vegetation in the study area were under natural weather conditions in a sub-humid equatorial region unlike the standard values that are normally computed under controlled conditions. Considering the amount of water lost through ET in the catchment, cropland had the highest mean volume/day during the study period. However, considering that part of the forest was converted to wooded grassland, bare and built up areas that have significantly lower ET rates than croplands and tea, the net water lost through ET in the catchment was less than when the forest was intact. The reduction of the amount of water lost through ET_a implies that there is more soil water available in the catchment.

Soil water

In general, there was significant alteration of soil properties within the farmlands with reduced soil organic carbon (SOC) and increased bulk density (BD) in the upper layers of soil (0-40 cm depth). Consequently, there were variations in soil water content across the different land use/cover types with the highest values found in the forest in the upper layers. It was noted that beyond 40cm depth in all the land use/cover types, the soil is clay therefore it distributes water in a similar way. The high soil water content in the forest is an indication that the undisturbed land cover has a higher water holding capacity than the disturbed (farmland). This study has successfully characterized soil water in a sub-humid catchment that has undergone significant land use/cover change. The study has made significant contribution to knowledge about the effects of conversion of forest to other land use/cover types on soil water variability. This is particularly where forest and grasslands are converted to croplands and grazed lands.

Runoff generation

The cropland in comparison to the other land use/cover types responded faster to rainfall and had higher surface runoff generation in a given rainfall event while there was a considerable delay in response by the forest and minimal runoff. In particular, the response of the catchment to runoff generation in the cropland land was 26 times more than that of the forest. This difference was attributed to the exposure of cropland to rain beating therefore sealing of the soil pores that lead to faster generation of surface runoff. The runoff generation variations in different land use/cover types is an indication that the continued reduction of the forest cover and the resultant increase of farmlands in the catchment (together with intensified use of land) have considerably altered the catchment response to rainfall.

8.2.4 Changes in streamflow characteristics

The analysis of long-term streamflow data revealed significant increasing trend of the river discharge for the period between 1965 and 2016. On further analysis, these increasing trends were attributed to significant increase of the base flow which resulted to increased minimum flows (dry season) over this period; maximum flows (wet season) had no significant change over the same period. The results further showed that there was significant shift in percentile values of the dry season flows in such a way that the period after extensive land use/cover change occurred (i.e. *post-impact*) were significantly higher than during the time that the catchment had minimal land use/cover change (i.e. *pre-impact*). The behaviour of the streamflow characteristics was attributed mainly to the reduced forest cover that has consequently reduced the amount of water lost through ET. Therefore, there is more water stored in the sub-surface to replenish the river during dry periods. However, the high runoff measured during the field experiments appeared to have no long-term effect on the maximum flows. This was attributed to the presence of wooded riparian land that allows infiltration into the soil.

8.3 Implications of the findings

The increasing human population and the associated activities on limited agricultural lands poses challenges on the effectiveness of the management of both the catchment and water resources.

- Apart from the knowledge of soil water variability in this catchment, the soil properties/ water data generated (at farm level) in this study would be useful for calibration and validation of hydrological models that can be used in studies in data scarce catchments.
- The amount of water lost through ET was investigated using remote sensing at a spatial resolution of 30 m that enabled the characterization of crop coefficients in the catchment. The characterization of crop coefficient in this study is important in establishing crop water use in a sub-humid catchment in the equatorial region for crops growing under natural conditions. The standard K_c values are normally established for temperate climates whose vegetation has different characteristics and the crops used are usually grown under controlled conditions. Further, in this study it was established that it is possible to estimate the volume of water lost through ET at a considerably fine spatial resolution (30m in this case).
- The changes in water balance components established at the finer spatial scales used in this study would not have been possible if they were studied at catchment or regional scales. These findings are important for effective catchment and water resource management.
- While conversion of forest to agricultural land was found to have resulted in increased surface runoff and reduced soil water content, there was significant increasing trend in the mean annual river flow. Moreover, the minimum flows and base flow had increasing trends. The implication of these observations is that reduced forest cover has reduced the amount of water lost through ET. The consequence of reduced ET and increased infiltration was observed to have increased dry season flows.

Therefore, through the use of remote sensing, GIS and field experiments, this study has greatly contributed to knowledge and understanding of the effects human activities have on the water balance of a catchment in a sub-humid equatorial region. This study thus forms a basis for further research on the influence of human activities on the hydrology of a catchment and effect of such changes on water resource management.

8.4 Recommendations

(a) Catchment and water resource management

Forest protection measures imposed by the catchment management in order to conserve them usually compel people to adopt permanent (continuous) cultivation. This form of land use alters the soil properties and soil water movement. Therefore, catchment managers should encourage farmers to adopt soil management strategies in order to improve on soils as they till the land to prevent the continued damage. Moreover, as policy makers encourage the increase in the proportion of forest cover through reforestation, they should consider integration of forest with wooded grassland; since wooded grassland has soil water retaining capacities similar to the forest but losses less water through ET. Socio- economic aspects such as the need for diversified fuels for energy use and alternative building materials that have led to continued usage of forest materials thus reducing the forest cover should be incorporated in catchment management.

As population continue to rise and land use intensification continues probably through introduction of new crops, the catchment managers and planners should embrace the use of remote sensing particularly the use of Landsat satellite images and surface energy balance models (e.g. SEBS) to estimate how water is being lost through ET from individual farms. By so doing new trends of water use by farmers are monitored and scientific solutions can be offered on how to optimize the use of water and land resources. To monitor soil water dynamics in a catchment this study recommends the use of soil models such the Hydrus-1D; the one-dimensional model that was found capable of replicating soil water dynamics in each of the land cover types in this study. This way the catchment planners could advice the people on the most appropriate land management practices for soil water retention.

(b) Further research

Most sub-humid catchments of the equatorial region are experiencing increased population and associated land use/cover changes due to increased human activities. A lot of the studies have not incorporated how human activities are influencing the catchment; particularly land use intensification that has the potential to alter hydrology. Hence, my recommendation is that similar studies be carried out in other catchments in this region so that the new dimensions of changing hydrology may be realized. With governments' effort to rehabilitate forests worldwide by planting more trees, this study recommends that more studies be done on the ET rates of the tree species planted in a catchment so as not to negatively impact on the streamflow. The outcome of this thesis showed that integration of forest cover with wooded grasslands has resulted to more streamflow especially during the dry season. The study also recommend that further research should investigate the combined effects of changes in land use/cover and partitioning of rainfall on soil loses as a consequence of increased runoff.

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