MODELLING THE HYDROLOGICAL RESPONSES TO CHANGES IN LANDUSE AND COVER IN THE MALABA RIVER CATCHMENT, EASTERN UGANDA

BY

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ABSTRACT

Hydrological responses vary from one catchment to another, depending on the nature of land use and cover changes. Modelling the hydrological responses to changes in land use and cover at different catchment spatial scales was the major focus of this study. This study assessed the hydrological responses attributed to changes in land use and extreme weather events resulting into increased sediment loading/concentration, rainfall-runoff generation/volume, streamflow fluctuation and modification of the river channel in the Malaba River Catchment, Eastern Uganda. The hydrological responses were assessed using hydrological models (IHACRES, SCS CN, and SHETRAN) to examine the effect of land use on soil physio-chemical properties susceptibility to rainfall-runoff generation and volume, frequency and severity of extreme weather events, changes in streamflow variations, sediment loading/concentration and river channel morphology. The preliminary study results showed that the frequency of extreme weather events reduced from 4-10 to 1-3 years over the catchment. The performance of the IHACRES model with a Nash-Sutcliffe Efficiency (NSE) of 0.89 showed that streamflow comparatively corresponded with the results obtained the drought indices in predicting the recorded events of severe drought (2005) and flood (1997). Changes in land use and cover types showed that the highest change in the gain of land was experienced from the agricultural land use (36.7%), and tropical forest (regeneration) (2.2%). The biggest losses in land were experienced in the wetlands (24.6%) and bushland and thickets (15.3%) land cover types. The SHETRAN model calibrated period had a NSE of 0.78 and 0.81 in the validation period showed satisfactory fits between the measured and simulated streamflow. The agricultural land use (crop growing) had a higher influence on the rainfall-runoff generation and increase in the streamflow than the tropical forest, and bushland cover types in the simulated period. Similarly, the curve number model estimated a comparatively higher surface rainfall-runoff volume generated from the agricultural land use (crop growing) (71,740 m^3) than in the bushlands and thickets (42,872 m^3) from a rainstorm followed by the tropical forest cover type. This was also reflected in the lower rates of saturated hydraulic conductivity from the agricultural land use (crop growing). The study also showed that human-induced sediment loading due to gold mining activities contributed a much higher impact on the concentration of suspended sediments and streamflow than sediments from rainfall-runoff from the sampled streams. The main contributor of human-induced sediments to the Malaba River were Nankuke River (130.6kg/annum), followed by Omanyi River (70.6kg/annum), and Nabewo River (66.8kg/annum). Human-induced sediment loading had a profound impact on the streamflow variations both in the dry and wet seasons from the sampled tributaries. Lastly, in regard to the effect of land use and cover types on the river channel morphology, tree plantation (cohesion=12, angle of internal friction=27) and bushland and thickets (cohesion=14, angle of internal friction=22) cover types had the most stable river banks compared to the wetland and agricultural land use and cover types that exhibited higher levels of sediment concentration.

Keywords: Extreme weather events, hydrological components, sediment concentration, rainfall-runoff generation, channel morphology, artisanal gold mining, River Malaba, Eastern Uganda

DECLARATION

I, BARASA BERNARD solemnly declare that this thesis was compiled and written by me. It has never been presented anywhere for any academic award or published in any peer reviewed journals. Therefore, all materials used from other sources are duly appreciated and properly acknowledged.

Monday, March 10, 2014

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BARASA BERNARD

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LIST OF ACRONYMS

Acronyms	:	Meaning
CDI	:	Combined Drought Index
IHACRES	:	Identification of unit hydrographs and component flows from rainfall,evaporation and streamflow data
SPI	:	Standardized Precipitation Index
CSS	:	Concentration of Suspended Sediments
NSE	:	Nash–Sutcliffe Efficiency
SHE	:	System Hydrologique European
PET	:	Potential Evapo–Transpiration
GUI	:	Graphical User Interface
NEMA	:	National Environmental Management Authority
FAO	:	Food and Agriculture Organisation
DEM	:	Digital Elevation Model
RS	:	Remote Sensing
GIS	:	Geographical Information Systems
DSOER	:	District State of Environment Report
DHSVM	:	Distributed Hydrology Soil Vegetation Model
RHESSys	:	Regional Hydro–Ecological Simulation System
TACD	:	Tracer Aided Catchment Model, Distributed
TOPLATS	:	TOPMODEL based atmosphere transfer scheme
SWAT	:	Soil Water and Analysis Tools
SLURP	:	Semi–Distributed Land Use–Based Runoff Processes Model
SCS	:	Soil Conservation Service
ANOVA	:	Analysis of Variance
CN	:	Curve Number
NDVI	:	Normalized Difference Vegetation Index
PDI	:	Precipitation Drought Index

TDI	:	Temperature Drought Index
VDI	:	Vegetation Drought Index
MODIS	:	Moderate Resolution Imaging Spectro–radiometer
NMMU	:	Nelson Mandela Metropolitan University
APA	:	American Psychological Association
SAGA	:	System for Automated Geoscientific Analyses
LDAS	:	Land Data Assimilation System
ENSO	:	El Nino–Southern Oscillation
TM	:	Thematic Mapper
ETM	:	Enhanced Thematic Mapper
UTM	:	Universal Transverse Mercator
PDSI	:	Palmer Drought Severity Index
SDI	:	Streamflow Drought Index
SRI	:	Standardized Runoff Index
BMI	:	Bhalme–Mooley Index
NDWI	:	Normalized Difference Water Index
SWSI	:	Surface Water Supply Index
CMI	:	Crop Moisture Index
PAC	:	Precipitation Anomaly Classification
RDI	:	Reclamation Drought Index
NRI	:	National Rainfall Index
SMDI	:	Soil Moisture Drought Index
SPEI	:	Standardised Precipitation Evapotranspiration Index
GPS	:	Global Positioning System

Chapter 1

General Introduction

1.1 Research background

1.2 Hydrological responses

Hydrological responses are intrinsically related to the spatial processes of the hydrological cycle (Beven, 1989; Fi, 1996; Boorman and Sefton, 1997; Uhlenbrook, 2004). The responses may vary over time-scales from seconds, to days or weeks, through years to decades, and have continuous feedbacks with the atmosphere (Arnell *et al.,* 1996; Lake, 2003; Poff *et al.,* 2010). However, this depends on the amount of precipitation, antecedent conditions, watershed characteristics, and the flow paths along, which water is delivered to the stream channel (Schulze, 2000; Ma *et al.,* 2010). Water that contributes to streamflow arrives in the channel along one or more of four generalized flow paths: (1) direct precipitation onto the stream channel, (2) overland flow, (3) shallow subsurface flow or through-flow, and (4) deep subsurface flow or groundwater. Rain intercepted directly by the channel becomes streamflow immediately (Dickinson *et al.,* 2004; Winkler *et al.,* 2010). This is usually a modest contribution to the total flow in a stream unless the surface area of the stream is large ($> 1\%$) relative to the area of its catchment (Winkler *et al.,* 2010).

Hydrological responses are highly influenced by changes in land use and land cover. The influences are determined through evaporation regimes, the degree and type of ground cover and surface runoff generation patterns (Fohrer *et al.,* 2001; Elfert and Bormann, 2010). In particular, plant physiology regulates transpiration, while canopy structure determines interception storage and throughfall. Rooting depth, density and structure affect plant water uptake and infiltration capacity. All these processes feedback to surface runoff and leaching, and therefore influence interflow and groundwater recharge (Breuer *et al.,* 2009). Conversely, the modification of local climate and alteration of the river bed elevation are some of the indirect effects of land use and cover changes (Weng, 2001). However, these effects are location specific and scale dependent (Chomitz and Kumari, 1998).

1.3 Land use and cover changes: a global issue and its impact

According to Di Gregorio and Jansen (2000), land cover describes the physical states of the land surface including cropland, forest, wetlands, pasture, roads and urban areas, whereas land use relates to the manner in, which these biophysical assets are used by humans (Cihlar and Jansen, 2001). Specifically, land use and cover changes are significant determinants of the water supply on its transit through a landscape (Mustard and Fisher, 2004). Land use and cover changes are mainly caused by the modification of biophysical or human demands that arise from changed natural, economic or political conditions (O'Callaghan, 1996; Qiang *et al.,* 2011) and the climate (Yang *et al.,* 2005). For instance, many parts in the Tropical Africa are affected by the intensive land use and cover changes for the last decades, particularly the conversion of land cover into agricultural land (Giertz *et al.,* 2005).

The continuous modification of natural vegetation by land use and cover options qualifies the view that land use and cover changes are a major issue for this century, because their consequences have stronger implications than those from climate change (DeFries and Eshleman, 2004; Young, 2006). Knowledge of changes in land use and cover is uninformative unless it is linked to its impact on resources (i.e. water resources, land among others). An assessment of land use and cover changes should therefore include, as much as possible, the impact of the change (Green *et a1.,* 1994). Precisely, the effect of changes in land use and cover on hydrology varies from one region to another. For instance, the hydrological simulation results of the sub-humid Tocantins River basin, found in the southern part of the Amazon basin indicated that complete deforestation increased the simulated annual mean discharge by 16 percent (Costa *et al.,* 2003). In the transboundary River Mara catchment of East Africa, the discharge reduced by 52 percent (7,245km^2)

between 1973 and 2000 due to the intensification of agricultural activities (Schellhorn *et al.,* 2008).

Examining the complexity of hydrological responses to land use and cover changes are pertinent endeavour whose understanding calls for a multidisciplinary approach. Initial efforts have focused primarily on biophysical properties (e.g. altitude, slope or soil type), given the good availability of such data (Veldkamp and Lambin *et al.,* 2001). The approach may include an assessment of the effect of extreme weather events, sedimentation, hydrological responses and river channel morphology. This is ought to help evaluate the catchment hydrology beyond streamflow, which is crucial in determining the spatially-explicit relationship between extreme events, configuration of land use and cover change and hydrological responses across a catchment (Thanapakpawin *et al.,* 2007). Therefore, by detailing how land use and cover changes influence hydrological responses, decision makers are in a better position to formulate policies that can mitigate the undesirable effects of future land use and cover changes on the streamflow from an informed perspective.

1.4 Hydrological models

Hydrological responses to changes in land use and cover may be investigated by the use of hydrological models (Legesse *et al.,* 2003; Thanapakpawin *et al.,* 2007) that are in existence today; though they differ mostly in the hydrological variables of concern and region of their applicability (Mwavu-Mutua and Klik, 2007). These models have been utilized to analyse the effect of land management practices on water quality; but they may also be useful to quantify the hydrological responses of a catchment attributed to different land use and cover options (Fohrer *et al.,* 2001). The models can also provide information about the behaviour of a catchment with the use of effective values of catchment characteristics. The effective values may be determined from model calibration using stream discharge that is being simulated.

It is also worthy to note that remote sensing (RS) and geographical information systems (GIS) techniques facilitate the modelling of hydrological responses to changes in land use and cover by pre-processing spatial datasets before there are incorporated in simulation models. RS and GIS systems have a data management capability useful in distributed hydrological models, which are best suited for the quantification of the heterogeneity in rainfall, topography and drainage features of a catchment (Umesh *et al.,* 2002). Recent developments of decision support systems based on GIS and distributed hydrological models continue to provide practical and useful tools to understand the physical and hydrological responses and effects (Fohrer *et al.* 2001; Badar *et al.,* 2013). It is however important to note that, there are limitations to modelling hydrological responses, since land use and hydrological models are accompanied by a high degree of uncertainty. This uncertainty is attributed to insufficient data availability or quality and its related space-time heterogeneity (data uncertainty), insufficient knowledge of the physics and the stochastic features of the processes involved, particularly during the extreme precipitation periods (process uncertainty), and simplifications inherent in the model structure (model uncertainty) (Niehoff *et al.,* 2002). The reduction in hydro-meteorological data uncertainly in modelling hydrological, responses and hydrological dynamics play as a medium for understanding both the conditions for interactions to take place and the results of such interactions (Woonsup and Deal, 2008). This is useful in water resources planning and prediction of hydrological responses from the routinely measured climate, sediment; river channel morphology and land use and cover data (Wooldridge *et al.,* 2001).

1.5 Problem statement

The effects of land use and cover changes on the hydrological responses result into increased sediment loading/concentration, streamflow fluctuations, rainfall-runoff generation and modification of river channel morphology, which are crucial in the field of hydrological research for a considerable period of time to date (Klaus *et al.,* 2003; Zhang *et al.,* 2007). This has been so, especially, in the bid to assess the direct and indirect effects of land use and cover changes on the hydrological cycle and surface water quality (Weng, 2001; Jan and Jeffrey, 2010). It is important to note that the effects of land use and cover changes are the only non-climatic factors that can explicitly explain the losses of about 30 percent of the average annual discharge of most catchments worldwide (Geist and Lambin, 2002; Santiago *et al.,* 2003). DeFries and Eshleman (2004) highlighted the importance of understanding the effect of land use and cover changes on water resources, which they identified as a key research area for the decades ahead. This is also confirmed by Giertz and DiekkrĂźger (2003) and Gumbricht *et al.* (2007), who pointed out that investigations on the hydrological responses due to changes in land use and cover are rare in the tropical regions.

In Uganda, the effects of land use and cover changes on the hydrological responses are manifested at different spatial scales. At the catchment scale, the Malaba River catchment experiences hydrological responses resultant into increase/decrease in streamflow, modification of river bed/channel (sub-catchment scale) and increased sediment loading/concentration (micro-catchment). The hydrological responses are triggered by the increasing human needs of land for agricultural expansion (crop growing), settlement, exploitation of mineral resources (Kayanja and Byarugaba, 2001), climate change, weak enforcement of environmental policies, and poverty (NEMA, 1997; Bernard *et al.,* 2010). However, these continue up to presently to modify the river channel morphology, increased sediment loading/concentration and changes in streamflow.

Previous studies that have encompassed the Malaba River catchment have been carried out in the broader Lake Kyoga catchment where the catchment is found and these have focused on the effect of rainfall trends on community preparedness (Kansiime *et al.,* 2013), climate variability (Lindenschmidt *et al.,*1998; Kigobe *et al.*, 2011) and water balance (Brown and Sutcliffe, 2013). However, modelling the hydrological responses and their dynamics has not been well documented in the Malaba River catchment. The Malaba River catchment was selected for this purpose because of it is significant water contribution to the Nile River basin. Much as the effects of land use and cover changes on the river catchment hydrology are interlinked with the impacts of climate change (Mango *et al.,* 2011), the effect of land use and cover changes are more significant than those attributed to climate change. However, modelling hydrological responses resultant from extreme weather events, changes in land use and cover resulting into increased sediment loading/concentration, streamflow, rainfall-runoff generation, and modification of river channel morphology have not been investigated yet in the Malaba River Catchment. Therefore, the foregoing discussions necessitated this current study and were the major motivation for this analysis.

The purpose of this study was to investigate the hydrological responses resulting from changes in land use and cover such as increased sediment loading, modification of river channel morphology, changes in streamflows and rainfall-runoff generation in the event of high frequency and severe extreme weather events recorded in the Malaba River Catchment.

1.6 Objectives of the study

1.6.1 Overall aim of the study

This study investigated the hydrological responses due to changes in land use and cover and extreme weather events resultant into increased/decreased sediment loading/concentration, modification of the river channel morphology, and variations in streamflows and generation of rainfall-runoff in the Malaba River catchment, Eastern Uganda.

1.6.2 Specific objectives

1. To assess the effects of extreme weather events on the streamflows of the Malaba River catchment. This objective was achieved through the use of drought indices (Combined Drought Index and Standardized Precipitation Index) in comparison with a hydrological model (IHACRES) in examining the frequency and severity of extreme weather events on the streamflow in the catchment.

2. To determine and estimate the effect of land use and cover change on the soil properties and their implications for the rainfall-runoff generation in the Malaba River catchment. This objective was achieved through soil analysis coupled with soil infiltration experiments, and use of a distributed surface hydrological model (Curve Number method) to estimate rainfall-runoff generated from each representative land use and cover option.

3. To assess the extent and effect of gold mining land use on sediment loading/concentration and their implications for the variations in streamflow of the Okame River micro-catchment. To achieve this objective, the study utilized a very high (TerraSAR-X imagery of 2008) and high resolution (Landsat TM/ETM+ imagery of 2012) images to quantify the extent of gold mining land use in the catchment. The TerraSAR-X

imagery was classified using an object-oriented classification algorithm; while the Landsat images were classified using a hybrid of per-pixel based and unsupervised image classification algorithms. Water (suspended sediments) and river bed deposit samples were collected and analysed using linear regression models.

4. To assess the effect of land use and cover change on the river channel morphology and their implications for the variations in streamflow of the Solo River Subcatchment. This objective was achieved through an assessment of the river bank stability through soil analysis, river channel analysis (cross section geometrical assessment), and sediment and bed load sampling.

5. To determine the effect of land use and cover changes on the streamflow of the Malaba River Catchment. To achieve this objective, two sets of multi-temporal Landsat images TM/ETM+ (1995 and 2012), were pre-processed and classified using the supervised image classification procedure in quantifying the extent of land use and cover changes. The linkage between changes in land use/cover and streamflow were determined using a SHETRAN hydrological model.

1.7 Structure of the thesis

The thesis is structured into eight chapters, which examine the hydrological responses due to extreme weather events and changes in land use and cover, and the resultant effects ranging from sediment loading and concentration, increased rainfall-runoff generation/volume and river channel morphology in the Malaba River Catchment. However, chapters 3 to 7 are presented as standalone articles in line with the stated objectives of the present study. They are laid out in publishable (journal article) format, based on catchment spatial scales.

Chapter one introduces the topic of hydrological responses, hydrologic models, land use and cover changes and their effect on the hydrological cycle.

Chapter two presents description of the Malaba River Catchment (i.e. location, climate, soil, hydrology, topography among others) and literature review. The chapter also presents the concept of hydrological modelling and hydrological model classifications, performance, application and their limitations. The chapter also shows highlights on the drivers of land use and covers changes and their consequences on hydrological responses, the role of remote sensing and GIS in land use and cover assessment.

Chapter three examines the frequency and severity of extreme weather events on the streamflow variations in the catchment. The Standardized Precipitation (SPI) and Combined Drought (CDI) Indices were used in comparison with the IHACRES hydrological model to assess the effect of extreme weather events on the streamflow.

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Chapter four reports on the effect of change in land use and cover types on the soil properties and their implications for the rainfall-runoff generation and estimation of runoff-volume in the Malaba River Catchment. Rainfall-runoff generation was examined through the use of double ring soil infiltration experiments and soil properties assessment. The runoff volume was estimated with the use of the SCS curve number model.

Chapter five assesses the extent of gold mining land use on sediment loading/concentration and their implications for the variation in the streamflow of the Okame River micro-catchment. This chapter presents the extent of gold mining land use quantified through the use remote sensing and GIS techniques. The chapter also presents the relationship between sediment concentration and streamflow through an application of regression models.

Chapter six shows the effect of land use and cover changes on the river channel morphology and their effect on the concentration/loading of sediments and streamflow variations in the Solo River sub-catchment. This chapter establishes the importance of the river bank stability in regard to the variation in streamflow and sediment loading/concentration.

Chapter seven investigates the effect of land use and cover changes on the streamflow of the Malaba River Catchment. This chapter relates to the frequency and severity of extreme weather events coupled with land use and cover changes in the variations of the catchment streamflow. The chapter results were achieved through an application of the SHETRAN hydrological model.

Chapter eight presents the synthesis of the major findings, conclusion and recommendations. This chapter synthesizes the findings presented from the analysis of land use and cover changes, extreme weather events responsible for rainfall-runoff generation, sediment loading/ concentration and river channel morphology in relation to the variation in the catchment streamflow. This chapter also presents recommendations based on the key findings and proposes new or future research areas/gaps to be undertaken in the promotion of sustainable use and management of land and water resources in the

Malaba River catchment.

1.8 Conceptual framework

The effect of spatial catchment scales on hydrologic variables (streamflow) is one of the major unresolved issues in hydrological sciences (McGlynn *et al.,* 2004). This study bridges this knowledge gap by investigating the hydrological responses to changes in land use and cover on the streamflow at the catchment, sub-catchment and micro-catchment scales in the Malaba River Catchment (Figure 1.1). These help to identify the relative hydrological effects of specific land uses/cover on rainfall-runoff generation, extreme weather events, channel morphology and streamflow production (Hollis, 1975). The scales are also rarely studied in hydrological studies in regard to sediment concentration and streamflow.

In this regard, the study examined the frequency and severity of extreme weather events, the effect of land use and cover changes, and rainfall-runoff generation on the streamflow at the catchment spatial scale (stream order 1; size 2,232 km^2). Examining these complexities at a catchment scale presented an opportunity to understand how the catchment responded after the application of drought indices, IHACRES model, SHETRAN model, and soil infiltration experiments in examining the hydrological responses to changes in land use and cover.

At the sub-catchment scale (stream order 2; size 71.8 km^2), the study assessed the effect of streamside (riparian vegetation) on the river bank stability and sediment concentration in relation to streamflow. Assessing the river bank stability and sediment concentration at this scale was ideal in understanding the dynamics of overland flow and the effect of land use and cover change in binding the soil particles together in bid to reduce the stream bank erosion, which in turn affects the streamflow. The effect of land use and cover change on the channel morphology was assessed through soil sampling along the river banks, river cross sectional analysis and sediment concentration sampling and assessment in relation to the variation in the streamflow.

At a micro-catchment scale (stream order 3; size 149.3 km^2), the extent and effect of gold mining land use on sediment loading and their implications for the variation in streamflow were determined through the use of remote sensing and sediment data. The suspended sediments and river bed deposit concentrations were examined at a tributary level from the Okame River Micro-catchment (Figure 1.1).

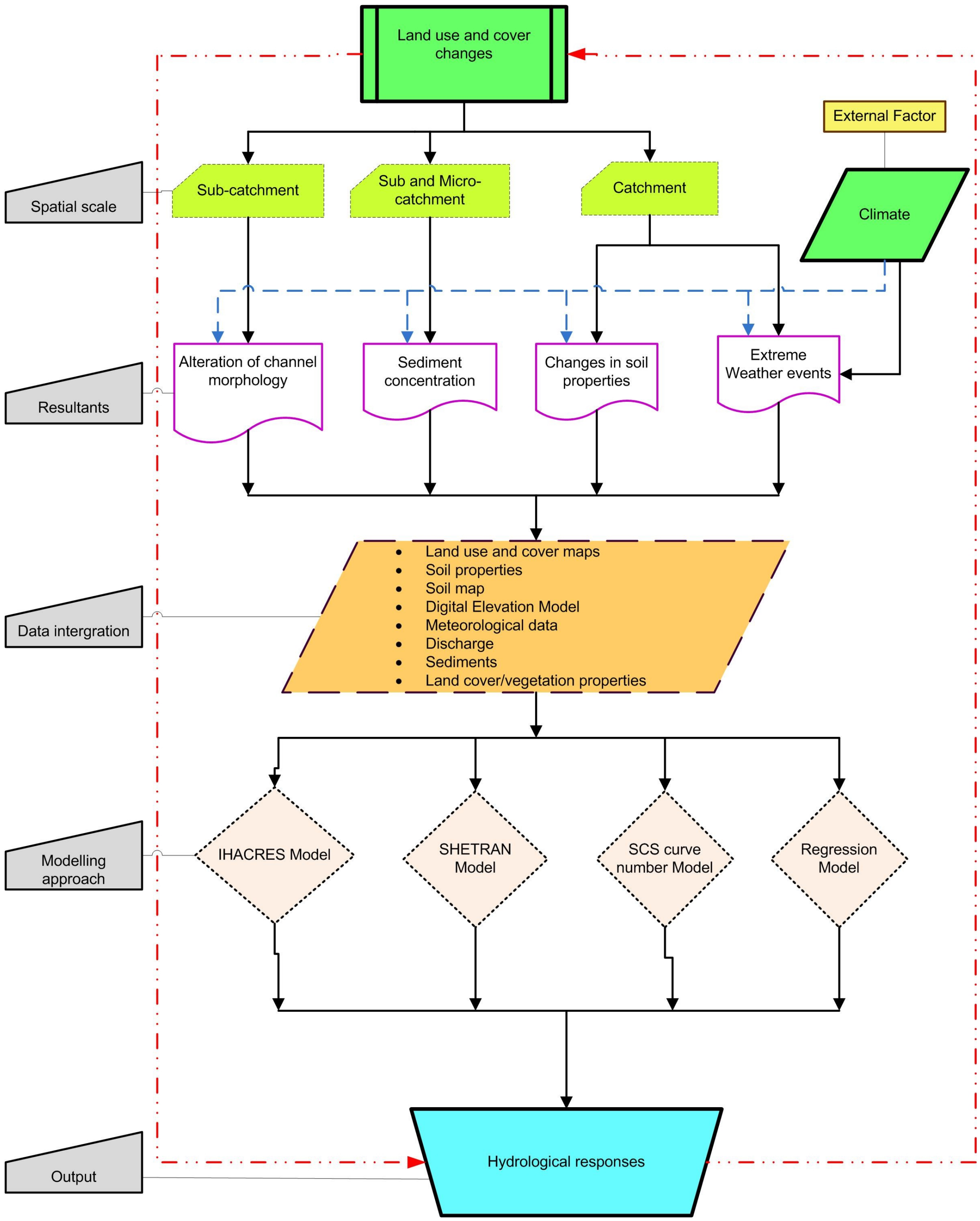

Figure 1.1: Conceptual framework

Chapter 2

Description of the Area of Study and Literature Review

2.1 Introduction

This chapter presents the general description of the area of study (Malaba River Catchment), literature review and a conclusion.

2.2 Description of the study area

2.2.1 Location of the Malaba River Catchment

Malaba River is a perennial river that is situated on the eastern part of Lake Kyoga (ILM, 2004). The Malaba River catchment is a mid-sized catchment, transboundary in nature, and falls within the Lake Kyoga Management Zone. The river originates from the slopes of Mount Elgon, from where it forms the border between Uganda and Kenya (Lakimo, 2004; Kizito and Ngirane-Katashaya, 2006). The size of the catchment is 2,232 km^2. About seventy percent of the river is situated in Uganda (midstream and downstream), while the remaining portion is in Kenya (upstream) (Figure 2.1). The catchment has a total of 32 sub-catchments with swamps originating along the main river and its tributaries.

In Uganda, the river flows through the districts of Tororo, Bugiri, Busia, Manafwa, Bududa, and Bugoma and Busia counties in Kenya before finally discharging into Lake Kyoga (NEMA, 2008). The other major tributaries of the Malaba River include Lwakhakha River, Malakisi River, Aturukuku River, Okame River, and Solo River. This catchment was chosen by this study because of its intrinsic land use and covers options that exhibited significant effects on the streamflow resulting from sediment loading, channel modification, and extreme weather events. Generally, catchments are useful units for hydrological response analysis because of their several physical characteristics and social aspects (Schreier *et al.,* 2003; Legesse, 2003).

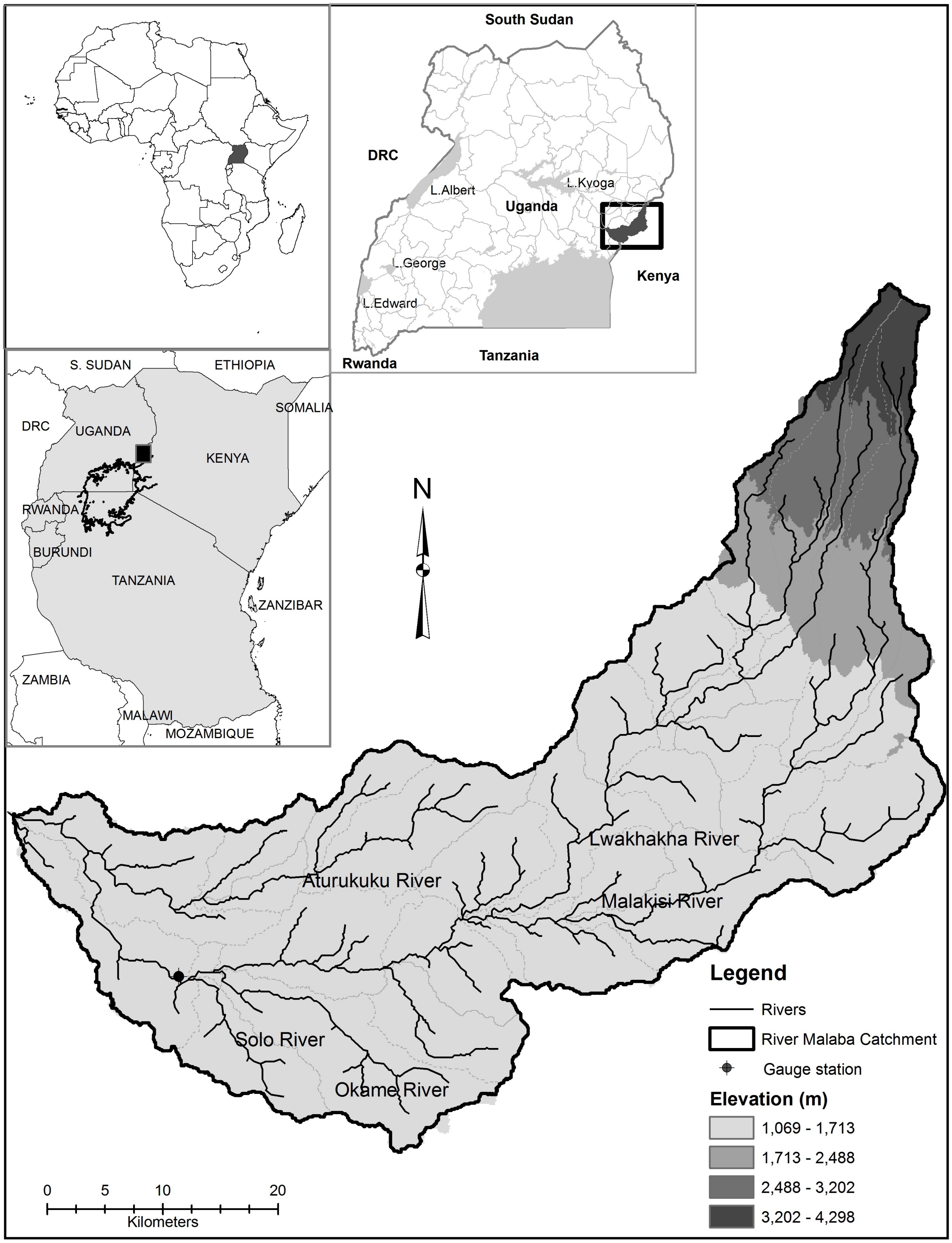

Figure 2.1: The Malaba River Catchment

2.2.2 Climate

The Malaba River catchment experiences a mean annual temperature of about 27.9 °C. The highest temperatures are experienced from January to March with 29.3 °C respectively. The minimum annual temperature is 15.9 °C experienced from March to May and October to December. The highest precipitation is received from March to May (280 mm/month, 240 mm/month) and August to November (183 mm/month, 170 mm/month). The driest months are January (71 mm/month) and July (81 mm/month); whereas, the potential evapotranspiration rates are highest in the months of January (148.8 mm/month) and March (148 mm/month). The lowest potential evapotranspiration rates are experienced in the months of May, June, July, and August with 114 mm/month respectively. The catchment water vapour is relatively high in the months of April and May with 20.3 hPa respectively and the lowest in January (16.9 hPa) and February (17.8 hPa). The speed of wind is also highest in January and February 7.92 km/h. This moves at a greater speed than in November and December (7.20 km/h), while the other months experience a wind speed of about 6.12 km/h.

2.2.3 Soils

The sandy-loams are found in the upland areas, while valleys are dominated by the clays. These soil types have a little difference in their defining soil-layer horizons. The soil types fall under a soil catena group of, Petric plinthosols, and Gleysols. The remaining soil types are under Lixic ferrasols, Acric ferrasols and Nitisols. These soil catena groups can be distinguished easily because they represent earlier stages of the weathering processes (NEMA, 1997).

2.2.4 Land use and cover

The Malaba River catchment is endowed with both natural and artificial vegetation types. These range from high altitudinal coniferous vegetation, tropical high forests, eucalyptus through swamps to savannahs. Subsistence agriculture is the major land use type carried out by nearly every household in the catchment. This mainly involves livestock rearing and crop growing in the bid to provide food and livestock products for both home consumption and sale in the nearby markets to meet the basic necessities. Other land use types covering a relatively large portion (40%) of the catchment land include: built-up areas, other infrastructures, mining among others.

2.2.5 Mineral resources

Gold, limestone, phosphates and sand are the major mineral types found and being mined in the catchment. Mining activities are carried out at both commercial and subsistence levels apart from sand, which is mined at subsistence level. Gold is largely mined in Busia district of Uganda, while limestone and phosphates in Tororo district. Sand is extracted from the Malaba River bottom and is sold in the nearby trading centres.

2.2.6 Land tenure

About, 90 percent of land holdings in the catchment are under the customary and freehold tenure, while the remaining 10 percent is under private leasehold or statutory leaseholds (DSOER, 2004).

2.2.7 Topography and geology

The catchment is hilly with undulating plains. The highest point (peak) is on Mount Elgon (about 4,298 metres above sea level), while the undulating plains are in the mid and downstream sections of the catchment. The Precambrian and Tertiary Pre-Elgon volcanic type of rocks underlie the entire catchment. The Precambrian rocks are of a basement complex, which includes a variety of granites, gneisses, quartzite and small areas of strong folded metamorphic rocks (DSOER, 2004).

2.2.8 Existing water supply schemes in the catchment

Malaba River provides both municipal and agricultural water to the surrounding districts (Busia, Mbale and Tororo). This river is the main source of raw water abstraction, which is situated 7 km south of Tororo town. On average, about 3,000m^3 per day of water is treated and pumped to the 4,000m^3 and 300m^3 in Tororo and Malaba Town. The municipal water supplies are managed by the Uganda National Water and Sewerage Corporation.

2.3 Literature Review

This section of literature review elucidates the broad theoretical and conceptual aspects of hydrological models and responses, concept of hydrology, classification of hydrological models, land use and cover changes and their dynamics, integration of remote sensing and geographical information systems in modelling hydrological responses. The conclusion presents the knowledge gaps filled by this study. However, each chapter has its own literature review section that further demonstrates the gaps in knowledge related to examining hydrological responses to changes in land use and cover in the catchment.

2.3.1 Hydrology

Hydrology can be defined as an interdisciplinary geoscience, which deals with the processes governing the replenishment and depletion of terrestrial water resources. It revolves around understanding and describing quantitatively physical, chemical and biological components and processes, which interact and operate at a wide range of spatio-temporal scales that are affected by human activities (Schulze, 2000; Savenije, 2009). The factors may affect a region's hydrology include weather (solar and earth radiation, temperature, humidity, wind), and precipitation (Linsley *et al.*, 1975; Beven, 1987).

2.3.2 Concept of hydrological modelling

Historically, hydrological modelling was undertaken to better understand the relationships between rainfall and runoff in the latter half of the 19^{th} century in response to three main engineering problems urban sewer design, land reclamation drainage systems design, and reservoir spillway design. It is conceivable, however that these types of engineering problems date back to before the Roman Empire, and that planners of that time dealt with similar issues at smaller scales (Hubbart, 2012).

Today, the concept of hydrological modelling is an indispensable tool for testing new hypotheses and obtaining a better understanding of hydrological responses and their interaction (Rosbjerg and Madsen, 2005; Aghakouchak and Habib, 2010). These may range from forecasts for the hydropower industry, public safety, agriculture to environmental monitoring (Berg and NystrĂśm, 2005). Therefore, hydrological models are attempts to represent the hydrological system from precipitation to streamflow in a mathematical form. The complexity of the models varies with the user requirements and the data availability. The models may vary from simple statistical techniques, which use graphical methods for their solution to physically-based simulations of the complex three-dimensional nature of a watershed (Smith *et al.*, 1994).

Modelling studies have advantages over basin experimental studies in being more flexible and rigorous in experimental design, and enabling mechanistic interpretation. In addition, the models are able to provide results immediately with much less cost in staffing and operation. Numerical simulations may depend on field experiments and observations for their construction, calibration, and validation and therefore cannot replace field experiments. However, numerical simulations can, in some cases, extend the scope and overcome the limitations of traditional field experiments, which are particularly true when addressing regional and global issues, including land use and climate change impacts (Li *et al.*, 2007).

Worldwide, hydrological models are used as tools to assist in addressing a wide spectrum of environmental and water resource problems in many climatic settings except the tropical regions; where hydrological modelling has lagged behind (Wurbs, 1998; Giertz and Diekkruger, 2003). Nevertheless, the hydrological models provide a framework for conceptualizing and investigating the relationships between climate, human activities (e.g. land use change) and water resources and have been applied for quantifying the impact of land-use change on hydrological components. Therefore, hydrological models are a useful means of assessing the effects of changes in land use and cover patterns resulting from policy decisions, economic incentives or economic structural changes. Recently hydrological simulation models have been widely used to quantify the influence of land use and cover change on the hydrologic cycle (Lin *et al.*, 2008). In this regard, the study adopted the modelling approach to assess the hydrological responses to changes in land use and cover on the Malaba River hydrological system.

2.3.3 Classification of hydrological models

Hydrological models may be categorized based on three decision rules: Does the model include randomness, spatial and temporal variation? (Kite and Pietroniro, 1996; Viessman and Lewis, 2003). In particular, the models can be classified into general categories, namely empirical, physically-based and lumped-conceptual models, elucidated below.

Empirical models are the simplest forms of numerical models to simulate streamflow as a direct relationship between it and other measured variable. The simplicity of this type of model makes it widely applicable but its usefulness is restricted by the end-product from the model. The frequently used example of a black box model is the unit hydrograph. However, the model relationships are based on empirical data, and not necessarily on the physical processes (Courault *et al.*, 2005; Davie, 2008).

Physically-based models are based on physical processes and are modelled on the understanding of physical mechanisms and often make large demands in terms of computational time and data requirements. These models offer increased explanatory and experimental power. However, because of the higher number of assumptions that are necessary, their predictive capacity is often equal or worse than that of empirical models (Beven, 1989; Grayson *et al.*, 1992).

Lumped conceptual models were the first attempt to reproduce the different hydrological processes within a catchment in a numerical form. Rainfall is added to the catchment and a water budget approach used to track the losses (e.g. evaporation) and movements of water (e.g. to and from soil water storage) within the catchment area. The term 'lumped'is used because all of the processes operate at one spatial scale - that is, they are lumped together and there is no spatial discretization. The scale chosen is often a catchment or sometimes sub-catchments. The term 'conceptual'is used because the equations governing flow rates are often deemed to be conceptually similar to the physical processes operating (Refsgaard, 1997; Davie, 2008).

Models can also be classified according to the type of equation used and the resulting output. Model results can be a singular, or a population of answers. Processes can be described either by deterministic or stochastic equations (Hughes, 1993). Deterministic models have just one possible outcome, whilst stochastic models have a population of answers (Yevjevich, 1987). In most cases, both types of equations occur within the same model. However, in the cases where the relevant information for parameterization is not available, some processes are better modelled by stochastic equations that could give an approximation for modelling purposes (Krzysztofowicz, 1999).

Based on the hydrological model classifications, the study adopted a mixture of lumped conceptual, surface and spatially distributed hydrological models to examine the hydrological responses attributed to land use and cover changes. The lumped conceptual model was chosen because of the capability of defining effective rainfall as the rainfall that is not lost to evapotranspiration and is therefore available for stream-flow (Post and Jakeman, 1996).

The spatially distributed hydrological models were chosen because they can address a range of environmental and water resources problems such as the spatially varying effects of land use or climate changes on the catchment behaviour, and to meet the request for more accurate predictions of streamflow at any point along the river system. In addition, Butt *et al.* (2004) found out that up to date the capabilities of spatially distributed models have not yet been fully exploited, primarily due to their computational, distributed input and parameter estimation requirements. However, the rapid increase in computer power, the development of efficient computational methods, the availability of sophisticated Geographical Information Systems, and the increasing wealth of spatial data of different types facilitate the proper calibration of these models, and consequently their use in making reliable predictions.

2.3.4 Descriptions of hydrological models appropriate for this study

Hydrological models are simplified mathematical formulations representing key processes of the hydrological cycle. The choice of a model to be used for a particular case-study depends on many factors, such as the study purpose, data availability and so on (Xu, 1999). For this purpose, a critical assessment of few hydrological models was made prior to their application in the modelling of hydrological responses to changes in land use and cover in the Malaba River Catchment. The reviewed hydrological models were as follows

The Distributed Hydrology Soil Vegetation Model (DHSVM)

The Distributed Hydrology Soil Vegetation Model (DHSVM) is a distributed hydrologic model originally developed to evaluate the effects of topography and vegetation on water movement through a watershed. Spatially distributed models such as DHSVM provide a dynamic representation of the spatial distribution of soil moisture, snow cover, evapotranspiration, and runoff production, at the scale of digital elevation model (DEM) pixel. DHSVM has been used to assess changes in flood peaks due to enhanced rain-on snow and spring radiation melt response, effects of forest roads and road drainage, and the prediction of sediment erosion and transport (Wigmosta *et al.*, 1994). The limited application of the DHSVM model in the tropical region is because of estimation of run-off based on the digital elevation model. This limitation made it unsuitable in modeling hydrological responses to changes in land use and cover in this study.

MIKE-SHE

MIKE SHE is a deterministic, distributed physically-based hydrological model (Refsgaard and Storm, 1995) capable of simulating water flow in all major components of the hydrological system at catchment scale. The model presents spatial variability in input parameters such as elevation, soil characteristics, land use, precipitation and potential evapotranspiration. The watershed is represented by two analogous horizontal-grid square networks for surface and groundwater flow components. These are linked by vertical columns of nodes at each grid representing the unsaturated zone. The hydrologic simulations consist of subcomponents describing the processes of evapotranspiration, overland and channel flow, unsaturated flow, saturated flow, and channel/surface aquifer exchanges. In MIKE SHE the catchment is represented in an integrated fashion by the major processes and their interactions. The MIKE SHE was not adopted by this study because it is limited in terms of studying the climate, and effects of land use and cover changes at a catchment scale.

Regional Hydro-Ecological Simulation System (RHESSys)

The Regional Hydro-Ecological Simulation System (RHESSys) is a hydro-ecological model designed to simulate integrated water, carbon, and nutrient cycling and transport over spatially variable terrain of small (first-order streams) to medium (fourth- and fifth-order streams) scales (Tague and Band, 2004). The model is structured as a spatially nested hierarchical representation of the landscape with a range of hydrological, micro-climate, and ecosystem processes associated with specific landscape objects at different levels of the hierarchy. This approach is designed to facilitate environmental analysis that requires an understanding of within-watershed processes as well as aggregate fluxes of water, carbon, and nitrogen.

The representation of the vertical soil profile, however, is based on a fairly simple two-layer model with a single unsaturated and saturated zone. Additional hydrologic stores include a litter layer, surface detention store, multiple canopy interception layers, and a snowpack. However, a hydrological model, such as RHESSys is intermediate in terms of complexity in regard to assessing catchment hydrological responses; and therefore it was not appropriate for this study.

Tracer Aided Catchment Model, Distributed (TAC-D)

The TACD (tracer aided catchment model, distributed) model is a conceptual rainfall-runoff model with a modular structure. It can be applied on an hourly basis, and is fully distributed, i.e. using 50 x 50 m^2 grid cells as spatial discretization. The water is routed between the cells, applying the single-flow direction algorithm (D8), which is suitable for the mountainous basin where the water flow direction is dominated by the steepest gradient. It is coded within the geographical information system (GIS) PC-Raster that offers a dynamic modelling language (Uhlenbrook *et al.,* 2004). The limited application of the TACD model to the mountainous catchments could not facilitate its usage in a catchment like the Malaba River catchment which lies in a larger area comprised of undulating plains.

TOPLATS

The TOPLATS model ("TOPMODEL based atmosphere transfer scheme) is a multi-scale model to simulate local to regional scale catchment water fluxes (Peters-Lidard *et al.,* 1997). It combines a "soil vegetation atmosphere transfer scheme"(SVAT) to represent local scale vertical water fluxes with the catchment scale TOPMODEL approach (Beven *et al.,* 1995) to laterally redistribute the water within a catchment. The raster based TOPLATS model considers vertical as well as horizontal water fluxes by coupling a SVAT-scheme (Soil Vegetation Atmosphere Transfer) and the TOPMODEL approach. Its process representation is mostly based on physical principles. Evapotranspiration is calculated by the Penman-Monteith approach or by solving the energy balance equation. Runoff generation is calculated from both; infiltration and saturation excess (Bormann, 2006). This study did not adopt the TOPLATS model because of its consideration of infiltration excess runoff which is not representative of the Malaba River catchment.

Soil Water and Analysis Tools (SWAT)

SWAT is a physically based model, was developed by USDA-ARS in the early 1990s for the prediction of the long-term impact of rural and agricultural management practices (such as detailed agricultural land planting, tillage, irrigation, fertilization, grazing, and harvesting procedures) on water, sediment and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions (Arnold *et al.*, 1998). SWAT takes into account surface runoff, percolation, lateral subsurface flow, groundwater return flow, evapotranspiration and channel transmission losses. Runoff volume is estimated by the modified SCS curve number method. Peak runoff predictions are based on a modification of the Rational Formula, while the watershed concentration time is estimated using Manning's formula, considering both overland and channel flow (Grizzetti *et al.*, 2003). Much as SWAT accounts for surface runoff, the model was not adopted by the study because the runoff model incorporated in SWAT is lumped at sub-basin level and not representative of runoff in the entire catchment. The model also has difficulties in reconciling rainfall in both dry and wet seasons (Levesque *et al.*, 2008). In addition, the SWAT model only works at a daily time step.

Semi-Distributed Land Use-Based Runoff Processes Model (SLURP)

SLURP (Semi-distributed Land Use-based Runoff Processes) is a conceptual model, which includes a full hydrological cycle simulation as well as the inclusion of man-made factors such as reservoirs, diversions and extractions and irrigation from surface and groundwater. The SLURP model divides a basin into many smaller sub-basins on the basis of topography. Each sub-basin is known as an aggregated simulation area since it, in turn, is subdivided into sub-areas of different land use. The aggregation by land area is to reduce computation time, while retaining physical plausibility. The SLURP model was not used by this study for, it aggregates land use and cover pixels into areas that are more convenient for modelling. In addition, the effects of land use and cover changes are not simulated with the same spatial resolution as would be in the fully distributed approach (Breuer *et al.*, 2009).

IHACRES Model

The IHACRES model (Identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data) consists of two modules: a non-linear loss module to convert rainfall to excess rainfall; and, a linear module to convert effective rainfall to stream-flow. Effective rainfall is defined as the rainfall that is not lost to evapotranspiration and is therefore available for stream-flow (Post and Jakeman 1996). The non-linear loss module uses temperature and rainfall to estimate a relative catchment moisture store index. This in turn determines the proportion of rainfall that becomes excess rainfall. Unit hydrograph approaches are used to identify the quick flow (runoff) and slow flow (base flow) components. The IHACRES model was utilized by this study because it requires minimal data input and has the potential to advance our understanding of streamflow patterns and predict how these may be altered by land use and extreme weather events (Scoccimarro *et al.,* 1999; Sloan 2000).

The conceptual IHACRES model extends unit hydrograph theory by assuming a linear relationship not only between effective rainfall and quickflow, but between effective rainfall and other identifiable hydrograph response components. The model consists of a nonlinear rainfall loss module which converts observed rainfall, r_k, at time step k, into effective or excess rainfall, u_k, and a linear module which converts the excess rainfall into observed streamflow, q_k. Usually the two modules use, in total, seven or eight parameters, also called dynamic response characteristics (Jakeman and Hornberger, 1993), to describe the way in which observed rainfall becomes observed streamflow. Effective rainfall is defined as that rainfall which eventually leaves the catchment as streamflow. As a result, all of the losses of water occur in the non-linear module. In the non-linear module, an antecedent precipitation index, s_k is calculated at each time step as an internal state variable.

The index s_k is given by

$$s_k = \frac{r_k}{c} + \left[1 - \frac{1}{T_w(t_k}\right] s_k - 1 \tag{1}$$

In Eq. (1), c is defined such that the total volume of modelled effective rainfall is equal to the total volume of observed streamflow. It may be regarded as the maximum volume of the non-linear catchment store, since when the volume of the non-linear store is equal to c (s_k = 1), all of the observed rainfall, r_k, becomes runoff; $t_w(t_k)$ is the time constant (days) of catchment losses at daily mean temperature t_k °C according to

$$T_w(t_k) = T_w exp(20f - t_k f) \tag{2}$$

In (2), t_w is the time constant (days) of catchment losses at 20°C and f is a factor describing the effect of a unit change in temperature on the loss rate. Effective rainfall u_k is then calculated according to

$$u_k = \frac{1}{2}(s_k + s_{k-1})r_k \tag{3}$$

Once the effective rainfall has been calculated, the total unit hydrograph is determined by parameterising and discretising the following linear convolution as a configuration of linear reservoirs:

$$y(t) = \int_0^1 h(t-s)u(s)ds \tag{4}$$

Where *y(t)* is observed streamflow, *u(s)* is effective rainfall and *h(t)* is the unit hydrograph. The parameters describing the unit hydrograph are determined by a simple refined version of the instrumental variable technique. Its advantages in this context are described in Jakeman et al. (1990).

Relationship between hydrological responses and land use and cover characteristics

The multiple regression model does two things that are very desirable. In prediction studies, multiple regressions make it possible to combine many variables to produce optimal predictions of the dependent variable. For instance for causal analysis, it separates the effects of the independent variables on the dependent variable so that you can examine the unique contribution of each variable.

In the last 30 years, statisticians have introduced a number of more sophisticated methods that achieve similar goals. These methods go by such names as logistic regression, Poisson regression, structural equation models and survival analysis. Despite the arrival of these alternatives, multiple regression has retained its popularity, in part because it is easier to use and easier to understand (Holder, 1998; Allison, 1999).

The model refers to Y as a linear function of the predictors, plus statistical noise

Multiple regression:

$$Y_i = \beta_0 + \beta_1(x1)_i + \beta_2(x2)_i + \beta_3(x3)_i + +\beta_k(xK)_i + \varepsilon_i \tag{1}$$

The coefficients (the β's) are non-random but unknown quantities. The noise terms ϵ_1, ϵ_2, ϵ_3,... ϵ_n are random and unobserved.

The study utilized a multiple regression model to quantify individual land use contributions of change in examining hydrological responses. Without accurate quantification, the impacts of change for some land use classes on the hydrologic responses may be exaggerated or understated, or even misinterpreted.

Soil Conservation Service (SCS) curve number method

The Curve Number method (SCS, 1972), also known as the hydrologic soil cover complex method, is a versatile and widely used method for runoff estimation. In this method, runoff is expressed by a numerical value varying between 0 - 100. For the past 30 years, the SCS method consistently gives usable results for runoff estimation (Bosznay, 1989; Hjelmfelt, 1991; Ponce and Hawkins, 1996).

Therefore, the study found the SCS curve number method appropriate for predicting runoff volume from the selected land use and cover types. The method is also one of the most popular methods for computing rainfall runoff volume from rainstorm. It is also popular because it is simple, easy to understand and apply and accounts for most of the rainfall runoff producing watershed characteristics such as soil type, land use, hydrologic condition, and antecedent moisture condition (Singh, 2003).

The basic assumption of the SCS curve number method is that, for a single storm, the ratio of actual soil retention after runoff begins to potential maximum retention is equal to the ratio of direct runoff to available rainfall.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

Where

Q is runoff (in)

P is rainfall (in)

S is the potential maximum soil moisture retention after runoff begins (in)

Ia is the initial abstraction in), or the amount of water before runoff, such as infiltration, or rainfall interception by vegetation; and Ia = 0.2S

The runoff curve number, CN, is then related

$$S = \frac{1000}{CN} - 10 \tag{2}$$

CN has a range from 30 to 100; lower numbers indicate low runoff potential while larger numbers are for increasing runoff potential.

SHETRAN Model

The SHETRAN system was developed by the Water Resources Systems Research Laboratory (WRSRL) based on the SHE (Systeme Hydrologique Européen) through the international collaboration between groups in the UK, Denmark, and France (Ewen, 1995). SHETRAN is a 3D, surface/subsurface, physically-based, spatially-distributed and finite-difference model for water flow, multi-fraction sediment transport and multiple, reactive solute transport in river basins. It gives a detailed description in time and space of the flow and transport in the basin, which can be visualized using animated graphical computer displays. SHETRAN represents physical processes using physical laws applied to a 3D finite-difference mesh to model the hourly flow and transport for periods of up to a few decades. Since the SHETRAN is a new model, its limitation needs to be discussed in the future worldwide applications.

The SHETRAN model was applied in this study because it gives a detailed description in time and space of flow and transport in a river catchment. This makes it a powerful tool for studying the environmental impacts of rainfall runoff/erosion, pollution and the effects of changes in land use and climate, and also studying surface water and ground water resources and management (Walsh and Kilsby, 2007). The SHETRAN model was adopted by the study because it is a powerful tool for studying hydrological responses and environmental impacts associated with land use and climate change (Birkinshaw, 2010).

Three main components lie at the core of SHETRAN, one each for water flow, sediment transport, and solute transport. Flow is assumed not to be affected by transport and sediment transport not to be affected by solute transport, so the three components lie in a natural hierarchy (Fig. 1).

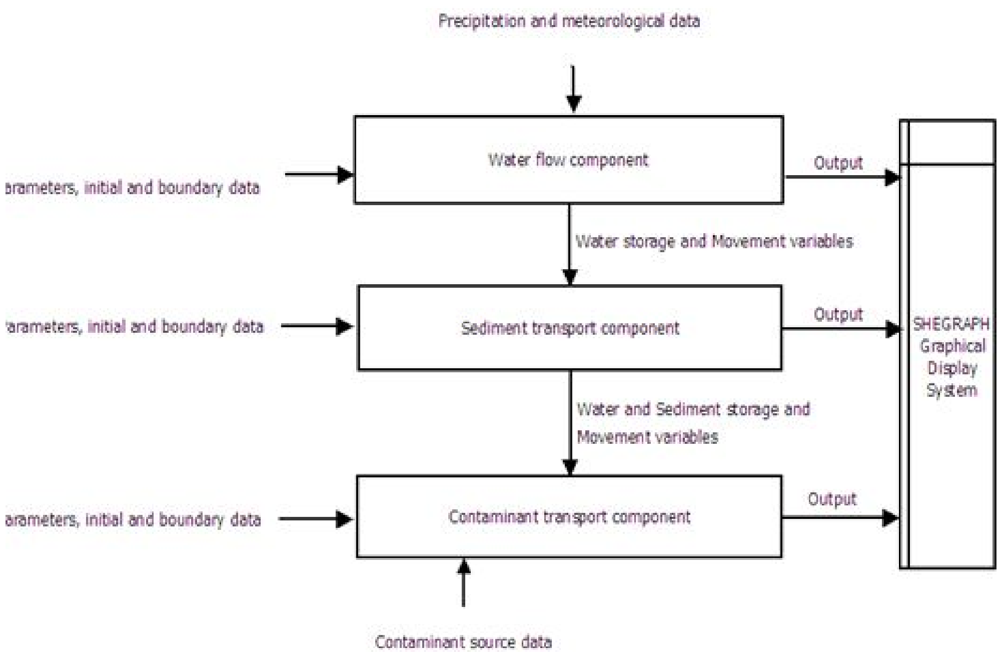

Figure 2.2: Information flows in SHETRAN model Source: Ewen et al., 2000

The components model physical processes (Table 2.1) represented by equations, most of which are partial differential equations (Table 2.2) and extensive data sets are required for model parameterisation (Table 2.3).

Component	Processes
Water flow: Surface water flow on ground surface and in stream channels; soil-water and ground-water flow in unsaturated and saturated zones, including systems of confined, unconfined, and perched aquifers	- Canopy interception of rainfall - Evaporation and transpiration - Infiltration to subsurface - Surface runoff (overland, overbank, and in channels) - Snowpack development and snowmelt - Storage and 3D flow in variably saturated subsurface - Combinations of confined, unconfined, and perched aquifers - Transfers between subsurface water and river - Water - Ground-water seepage discharge - Well abstraction - River augmentation and abstraction - Irrigation
Sediment transport : Soil erosion and multifraction transport on ground surface and in stream channel	- Erosion by raindrop and leaf drip impact and overland flow - Deposition and storage of sediments on ground surface - Total-load convection with overland flow - Overbank transport - Erosion of river beds and banks - Deposition on river bed - Down-channel advection - Infiltration of fine sediments into river bed
Solute transport : Multiple, reactive solute transport on ground surface and in stream channels and subsurface	- 3D advection with water flow - Advection with sediments - Dispersion - Adsorption to soils, rocks, and sediments - Two-region mobile/immobile effects in soils and rocks - Radioactive decay and decay chains - Deposition from atmosphere - Point or distributed surface or subsurface sources - Erosion of contaminated soils - Deposition of contaminated sediments - Plant uptake and recycling (simple representation only) - Exchanges between river water and river bed

Table 2.1: Main processes represented in SHETRAN

Component	Processes
Subsurface flow	Variably saturated flow equation (3D) (P)
Overland flow	Saint-Venant equations, diffusion approximation (2D) (A)
Channel flow	Saint-Venant equations, diffusion approximation (flow in a network of 1D channels) (A)
Canopy interception and drip	Rutter equation (A)
Evaporation	Penman-Monteith equation (PME) (or as fraction of potential evaporation rate) (A)
Snowpack and melt	Accumulation equation and energy budget melt equation (or degree-day melt equation) (A)
Overland sediment transport	Advection-dispersion equation (2D) with terms for deposition and erosion by raindrop and leaf drip impact and overland flow (W)
Channel sediment transport	Advection-dispersion equation (transport in network of 1D channels)with terms for deposition and erosion and for infiltration into bed (W)
Land surface and subsurface solute transport	Mobile/immobile advection-dispersion equation (3D) with terms for adsorption, dead space, radioactive decay, erosion of contaminated soil, deposition of contaminated sediments, plant uptake, and deposition from above (E)
Channel solute transport	Advection-dispersion equation (transport in network of 1D channels) with terms for adsorption to sediments, radioactive decay, erosion and deposition of contaminated bed materials, overbank ,transport and deposition from above (E)

Note: (A) = Abbott et al. (1986b); (E) = Ewen (1995);(P) = Parkin (1996);and(W) = Wicks and Bathurst (1996) and Purnama and Bathurst (1991).

Table 2.2: Main processes represented in SHETRAN

Component	Processes
Water flow	- Precipitation and meteorological data for each station - Station numbers for each column and river link - Size and location of columns, river links, and finite-difference cells - Soil/rock types and depths for each column - Land-use/vegetation for each column - Man-controlled channel flow diversions and discharges - Rates of borehole pumping, artificial recharge, flow diversions, and so forth - Initial hydraulic potentials for subsurface - Initial overland and channel flow depths - Initial snowpack thicknesses and temperatures - Boundary hydraulic potentials (or flow rates) - Boundary stream inflow rates - Canopy drainage parameters and storage capacities - Ground cover fractions - Canopy resistances and aerodynamic resistances (for PME) - Vegetation root density distribution over depth - Porosity and specific storage of soils/rocks - Matric potential functions for soils/rocks - Unsaturated hydraulic conductivity functions for soils/rocks - Saturated hydraulic conductivity of soils/rocks - Snow density, zero-plane displacement, and roughness height
Sediment transport	- Raindrop size distribution - Drop sizes and fall distances for canopy drainage - Proportion of canopy drainage falling as leaf drip - Initial thickness of sediments and channel bed materials - Sediment concentrations in waters entering via inflowing streams - Sediment porosities and particle size distributions - Erodibility coefficients
Solute transport	- Initial concentrations in surface and subsurface waters - Concentrations in rainfall - Dry deposition rates - Concentrations in flows entering at boundaries - Dispersion coefficients for soils/rocks - Adsorption distribution coefficients (and exponents, if nonlinear) - Mobile fractions for soils/rocks - Fractions of adsorption sites within mobile regions in soils/rocks - Exchange coefficients for mobile and immobile regions in soils/rocks - Decay constants (e.g., for radioactive decay) - Plant-uptake constants

Table 2.3: Main data for physical properties and initial and boundary conditions in SHETRAN model

2.4 The Role of remote sensing and GIS in hydrological modelling

Liu *et al.,* (1999) categorized applications of remote sensing in hydrological studies and water resources management as follows: (i) using remote sensing imagery directly to identify hydrologic important spatial phenomena; (ii) using processed remote sensing data, such as precipitation, in hydrological models; (iii) using multispectral data, such as vegetation (land cover) types and density, to quantify surface parameters; (iv) direct calculation of evapotranspiration distribution in terms of spectral data of satellite remote sensing based on surface energy balance, (v) using remote sensing derived fields, such as soil moisture, to improve model simulations through data assimilations; and (vi) validating model simulations using remote sensing data (Ritchie and Rango, 1996).

Land use and cover changes often reflect the most significant impact on the environment due to human activities or natural forces and that remote sensing can be an appropriate tool for getting wide impression on land cover change. It is now widely accepted that information generated from remotely sensed data is useful for planning, and decision making (Zhou and Sun, 2008). Geographical information systems (GIS) have a long tradition of integration with hydrological modelling (Martin *et al.,* 2005). This typically has involved a loosely coupled integration between GIS and hydrological models, where the GIS performs data pre-processing and visualization. This approach works, but there are drawbacks namely i) the interface is typically dedicated to a hydrological model with specific data needs and program control, and ii) the software cannot be easily integrated with other GIS technology (Newby and Pullar, 2009). The use of GIS in hydrological modelling allows us also to analyse a great amount of spatial-related physical data and to account for the spatial variation of model parameters and processes at a detailed resolution (Liu *et al.,* 1999; Beven 2000; Melesse and Shih, 2002).

Remote sensing and GIS have provided a more effective and less costly way to study hydrologic systems. In many applications, results from remote sensing and/or GIS analyses serve as input into hydrological models (Appel, 2002). Remote sensing enables the mapping, classification and monitoring of land cover that is required in many hydrological models. One of the typical applications of GIS is the use of a digital elevation model (DEM) for the extraction of hydrologic catchment properties such as elevation, slope, flow accumulation and direction, and the delineation of the catchment boundary (Tarboton, 2003).

The study also processed topographical spatial data with the use of remote sensing and GIS techniques prior to their incorporation into the hydrological models. The processed spatial datasets included land use and cover map, soil map, DEM. The techniques were also used to quantify the extent of gold mining activities in the catchment.

2.5 Land use and cover changes: definition and drivers

The term ‘land use’ is used to describe human uses of the land, including actions that modify or convert land cover from one type to another. Examples include categories such as human settlements (e.g. urban and rural settlements), agriculture (irrigated and rain-fed fields), national parks, forest reserves, and transportation and other infrastructure. The term “land cover”refers to the vegetative cover types and other surface cover that characterize a particular area. Examples include forest, savannah, and desert, among others. Under such categories we can have more refined categories of specific plant communities, e.g. shrub-lands, mangroves, seasonally flooded grassland, among others (Turner and Meyer, 1994).

The analysis of land use change revolves around two central and interrelated questions “what drives/causes land use”and “what are the environmental and socio-economic effects of land use change”. The precise meaning of the “drivers”or “determinants”of land use is not always clear. However, there are two main categories widely accepted biophysical and socioeconomic drivers (Lambin, 1997; Verburg *et al.,* 2004; Koomen and Stillwell, 2007). The biophysical drivers include characteristic and process of the natural environment such as: climatic variation, landform, and geomorphic process, plant succession, soil types and process, drainage pattern among others. The socio-economic drivers comprise demographic, social, economic, technological, market, political and institutional factors and their processes (BiĂ¨i?k *et al.*, 2001; Rounsevell *et al.*, 2003).

Land use and cover changes are driven by the interaction in space and time between biophysical and human dimensions. The potential large impact of land use and cover changes on the physical and social environment has stimulated research in the understanding of land use and cover change, and its main causes and effects (Zeleke and Hurni, 2001; Veldkamp and Verburg, 2004; Mwavu and Witkowski, 2008). Land use and cover changes are currently very rapid and their consequences are more evident in the tropical regions (Ramesh, 2001). For example, the conversion of cropland to urban area due to urbanization, as well as changes within classes such as a change of crops to crop rotations. Particularly in regions where water availability is limited, land use and cover changes could result in an increase of water scarcity and thus contribute to a deterioration of the standard of living (De Sherbinin, 2002).

2.6 Consequences of changes in land use and extreme weather events on the hydrological responses

Knowledge of changes in land use and cover alone is not sufficient unless it is linked to the impact on the environmental responses.

2.6.1 Extreme weather events

Global climate projections indicate that precipitation intensity is likely to increase and that resultant flooding is expected to be more severe. Floods with differing sizes and durations are likely to impact riparian systems in different hydrologic ways (Simpson *et al.*, 2013). Streamflow seasonality varies regionally, depending on the timing of maximum precipitation, evapotranspiration, and contributions from snow and ice (Ropelewski and Halpert, 1987; Dettinger and Diaz, 2000). There is a strong relationship between streamflow and the warm (El nino) phase of the El Nino/Southern Oscillation (ENSO) cycle (Dracup and Kahya, 1994) over East Africa.Â For example, frequency distributions of daily precipitation in winter and daily streamflow from late winter to early summer, at several hundred sites in the western United States, exhibit strong and systematic responses to the two phases of ENSO. Most of the streamflow considered are driven by snowmelt (Cayan *et al.,* 1999). Streamflow is more variable from year to year in dry regions of the southwest United States and Mexico, the Sahel, and southern continents, and it varies more (relatively) than precipitation in the same regions. However, tropical rivers have the steadiest flows (Dai *et al.,* 1998; Dettinger and Diaz, 2000).

Furthermore, the effects of a change in the frequency of high rainfall will depend not only on the change in rainfall characteristics but also on the characteristics of the catchment. For instance, small catchments with impermeable soils will be very responsive to short-duration intense rainfall; larger catchments, and those with more permeable soils, will be sensitive to longer-duration storm rainfall totals and general catchment wetness (Ropelewski and Halpert, 1987; Arnell *et al.,* 1996; Dettinger and Diaz, 2000).

In addition, a decrease in average total rainfall, an increase in the frequency of dry spells due to a decline in rain-days, and an increase in potential evapotranspiration due to higher temperatures have the potential to increase drought frequency and severity and to extend their effects into less-vulnerable areas. Increases in the frequency and magnitude of large rainfall events may result in reduced drought potential if they result in higher soil moisture levels and groundwater recharge. However, an assessment of the frequency and severity of droughts on the hydrological components has received little attention (Arnell *et al.,* 1996) especially in Uganda's catchments.

Therefore, the study assessed the frequency and severity of extreme weather events using drought indices in comparison with a hydrological model to bridge this knowledge gap in assessing their impact on the streamflow.

2.6.2 Streamflow variations

Land use and cover have generally been considered a local environmental issue, but there are becoming forces of global importance. Worldwide changes to forests, farmlands, waterways, and air are being driven by the need to provide food, fiber, water, and shelter to more than six billion people (Foley *et al.*, 2005). Land use and land cover changes greatly impact annual and seasonal variations of streamflow (Guo *et al.*, 2008). The effect of land use and cover changes on the streamflow is one of the most important environmental problems. Expanding cities due to economic and population growth or both often comes at the expense of increased risk of flooding and decreased water quality and quantity (Kimaro *et al.*, 2003).

Sediments delivered to streams create turbid water, or settle to the stream bottom (Zimmerman *et al.*, 2003). The key drivers of increased sediment loads include land clearance for agriculture and other facets of land surface disturbance, including logging activity and mining. The contemporary data on the sediment loads of rivers provide clear evidence of significant recent changes in the sediment fluxes of several rivers in response to human impact (Walling, 2006).Â Therefore, the study of runoff generation and sediment loading in an agricultural catchment is essential for the protection of the environment and ecosystems (Jordan *et al.*, 2005).

The effects of changes in land use and cover on the seasonal variations of streamflows were assessed through hydrological modelling (using a spatially distributed SHETRAN hydrological model) in the Malaba River catchment.

2.6.3 River channel morphology

Channel morphology is dynamic, changing both spatially and temporally in response to controlling factors such as changes in hydraulic discharge, sediment delivery and stream bed and stream bank roughness (Montgomery and Buffington, 1998). The channel can adjust to these changes in a number of ways, including changes in channel width and depth, channel cross sectional shape, channel gradient, bed material composition, channel sinuosity, and bed form composition.

Geomorphological systems are often viewed as being in a stable form and tend to be accepted in their recent condition as natural and proper. Channel changes, e.g., narrowing, widening, shifting, aggrading, or degrading, are often viewed negatively. This is because they commonly create conflicts with human uses developed along the river. Channel incision threatens bridges, channel migration erodes agricultural lands, aggradation reduces channel capacity and thereby increases flood risk, and increased runoff in urbanized areas sets off a round of incision and widening that threatens the new infrastructure (Kondolf *et al.,* 2002; LiĂŠbault, *et al.,* 2005).Â A geomorphological perspective help to define policies with an appreciation for the dynamic nature of river channels (Montgomery and Buffington, 1997)

The changes in land use and cover on the channel morphology are reflected in their contribution to reinforce the river bank stability by providing root reinforcement and increasing shear strength, particularly in non-cohesive alluvial bank materials. The changes are also an important source for channel roughness assessment (Abernethy and Rutherford, 1999).

Therefore, it is important to understand the interactions between channel stability and catchment changes i.e. land use and cover (Rosgen, 1985; Lancaster and Hildrew, 1993). For example, if catchment changes produce an increase in streamflow, alluvial stream channel dimensions will change to accommodate the increases. That is, the channel enlarges and its bankfull dimension grows wider through bank erosion and lateral extension (Rosgen and Silvey, 1996; Newson and Newson, 2000). Forested stream banks, compared to grass ones, can destabilize stream channels by promoting erosion (Trimble, 1997).Â However, this may result into adverse economic and environmental consequences (Gaeuman *et al.,* 2005). This study also investigated the interaction between the river bank stability and land use and cover changes in influencing streamflow variations, channel morphology and sediment concentration.

2.6.4 Rainfall runoff generation

The soil physio-chemical properties are crucial inputs needed to assess the effects of land use and cover on rainfall runoff generation. Assuming that there are no significant effects from other factors that control soil hydrodynamics such as crusting in sandy soils and micro-aggregation in clay soils, sandy soils allow a high rate of water infiltration and produce less runoff, while soils consisting of poorly drained clay soils allow a low infiltration and produce more runoff (Geza and McCray, 2008). Furthermore, simulation of hydro-ecological responses over meso-scale watersheds requires information on the spatial distribution of soil hydraulic properties, as well as rooting depths, which affect water available for vegetation use (Zhu and Scott-Mackay, 2001).

However, a soil's inherent erodibility, which is a major factor in erosion prediction and land use planning, is a complex property dependent both on its infiltration capacity and on its capacity to resist detachment and transport by rainfall runoff (Wischmeier and Mannering, 1969). Soil-surface seals and crusts resulting from aggregate breakdown may reduce the soil infiltration rate and thus induce erosion by increasing runoff. For example, the cultivated loess areas of north-western Europe are particularly prone to these effects, which results into increased streamflow variations (Le Bissonnais *et al.*, 1995).

On this note, the study evaluated and estimated the effect of land use and cover change on the soil properties and their implications for the generation of rainfall-runoff and volume using both soil infiltration experiments and the curve number model. This approach was appropriate because hydrological response analysis often involves the evaluation of soil, water infiltration, and conductivity, storage, and plant-water relationships. Therefore, defining the hydrological soil and water effects requires estimating soil water characteristics for water potential and hydraulic conductivity using soil variables such as texture, organic matter (OM), and structure (Saxton and Rawls, 2006). In addition, the simulation of soil, water and evapotranspiration using physically based models varies in both complexity of processes modelled and in parameterization of soil and root properties (Federer *et al.*, 2003).

2.7 Conclusion

Hydrological models often provide a framework for conceptualizing and investigating relationships between streamflow and land use and cover changes. Therefore, understanding this relationship requires an application of a spatially distributed hydrological model in regard to the time and space of streamflow. Much as the applications of the SHETRAN hydrological model are rare in the tropical regions.

The review also demonstrates that streamflow seasonality varies from one region to another, especially, in regard to the frequency and severity of extreme weather events. This prompted the study to use both drought indices and a hydrological model to determine frequency and severity of extreme weather events in relation to the variations in the streamflow. The use of drought indices in comparison with a hydrological model to assess the effect of extreme weather events on the streamflow is also rarely carried out in many hydrological studies.

In addition, the soil physio-chemical information is one of the most crucial inputs needed to assess the effects of land use and cover on rainfall runoff generation. Therefore, the study assessed the effect of existing land use and cover types on the soil physio-chemical properties and their implications for the rainfall-runoff generation using soil infiltration experiments, which are rarely applied in the tropical regions in examining the susceptibility of soil to rainfall-runoff.

Geomorphological systems are often viewed as being in a stable form and tend to be accepted in their recent condition as natural and proper. Hence, their investigation in relation to land use, river bank stability and streamflow variation are rarely documented.

The present study examined the influence of land use and cover change on the river bank stability, sediment concentration and streamflow to bridge this knowledge gap.

Sediments delivered to streams can either be suspended and bed load. The key drivers of increased sediment loads include land clearance for agriculture and other facets of land surface disturbance, including logging activity and mining. This study compares both the natural and human induced sediment loading/ concentration in regard to the variations of streamflow in the catchment. This study further investigated the extent of gold mining land use and its impact on sediment loading and streamflow. Both the extent and sediment concentration in relation to streamflow are rarely studied together.

Chapter 3

Assessing the effect of extreme weather events on the streamflow of the Malaba River Catchment, Eastern Uganda

This chapter is based on:

Bernard, B., Vincent, K., Frank, M., & Anthony, E. (2013). Comparison of extreme weather events and streamflow from drought indices and a hydrological model in River Malaba, Eastern Uganda. *International Journal of Environmental Studies*,**70** (6), 940-951. DOI:10.1080/ 00207233.2013.862463.

Abstract

The study assessed the frequency and severity of extreme weather events (floods and drought) on the streamflows of the Malaba River using drought indices (Combined Drought Index and Standardized Precipitation Index) and a hydrological model (IHACRES -Identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data). The results showed that extreme weather events (floods and drought) frequency had reduced from 4-10 to 1-3 years over the catchment. The CDI was a better predictor of drought events (2005-2006) than the SPI, which was better for flood events (2006, 1997 and 2008) in the catchment. The performance of the IHACRES model (Nash-Sutcliffe Efficiency of 0.89) showed that streamflow corresponded with the results obtained from the drought indices especially during the recorded events of severe drought (2005) and flood (1997). The events corresponded with the stream peak flows. These events coincided with the El-Nino events that were recorded in Uganda.

Keywords: CDI, SPI, IHACRES, Streamflow, Floods, Drought

3.1 Introduction

Extreme weather events (drought and floods) affect resources such as water, agriculture and other aquatic ecosystems (Attril and Power, 2000; Hege *et al.,* 2001; Nalbantis and Tsakiris, 2009). These events occur when water availability is significantly below or above normal levels over a long period and cannot meet demand (Redmond, 2002). These events are frequently aggravated by human activities such as change in land use (Ma *et al.,* 2010) caused by rapid population growth, agricultural expansion, and increased demand for water (Mishra and Singh, 2010). Extreme weather events can be characterized according to the purpose, region of study, and the availability of data (Smakhtin and Hughes, 2004; Fleig *et al.,* 2006; Zeng *et al.,* 2008; Acharya *et al.,* 2011). Drought indices have been classed into four categories; namely, meteorological, agricultural, hydrological and socioeconomic (Nakbakht *et al.,* 2012). These indices (Tigkas, 2008) provide quantities for determining the onset and end of a drought event, in addition to the level of drought severity (Tabari *et al.,* 2013).

Drought indices are used for making decisions on water resource management. Many drought indices exist; e.g., the Palmer Drought Severity Index (PDSI), Streamflow Drought Index (SDI), Standardized Runoff Index (SRI), Bhalme-Mooley Index (BMI), Standardized Precipitation Index (SPI), Normalized Difference Water Index (NDWI), Crop Moisture Index, Surface Water Supply Index (SWSI), Precipitation Anomaly Classification (PAC), Reclamation Drought Index (RDI), National Rainfall Index (NRI), and Soil Moisture Drought Index (SMDI). These have been described by many scholars (Panu and Sharma, 2002; Khan *et al.,* 2008; Tigkas *et al.,* 2012).

The SPI is more suitable for monitoring droughts in East Africa than the PDSI and BMI because of a few required data inputs (Hayes *et al.,* 1999; Ntale and Gan, 2003). Most studies have assessed drought conditions at both regional and national scale. For instance, rainfall over Uganda exhibits a large spatial and temporal variability. This has been attributed to the existence of large and local scale systems, such as inland water bodies, which include Lake Victoria and Lake Kyoga, and the complex topography, such as Mt. Elgon (Ogwang *et al.,* 2012). The variability of extreme weather events is sometimes attributed to El Nino Southern Oscillation (ENSO), which originates in the Pacific Ocean and has wide ranging consequences for weather around the world (Kovats *et al.,* 2003). Nevertheless, there is a need to understand extreme weather events at a local scale, viz. the catchment scale (Paturel *et al.,* 2003).

Streamflow is generated chiefly by processes operating beyond perennial stream channels (Hewlett and Hibbert, 1967; Kokkonen *et al.,* 2003 which justifies a detailed study of how streamflow is affected by extreme weather events. The results from drought indices and hydrological model can be compared to examine the frequency and severity of extreme weather events in a catchment. In this aspect, several physically based hydrological models are already in use, or are currently being evaluated to assist planners in assessing the influence of different land use scenarios on streamflow such as HSPF (Donigian, 2002), SWAT (Arnold *et al.,* 1998), and SHETRAN (Ewen *et al.,* 2000) but they do not comprehend the influence of extreme weather events on streamflow. They are also are criticized for being over-parameterized. Accordingly, a simple IHACRES model is suitable to assess the relationship between extreme weather events and the streamflow because of its capacity to predict long-term natural variability of runoff from daily rainfall and evaporation (Hansen *et al.,* 1996).

Therefore, the purpose of this study was to assess the effect of extreme weather events on the streamflow by comparing the performance of drought indices (combined drought index and standardized precipitation index) and a hydrological model (IHACRES) in characterizing their frequency and severity in the Malaba River Catchment. This ought to help solve a number of engineering and environmental problems, such as the construction of bridge structures, flood control, water quality control, and provision of boundary conditions for models dealing with extreme weather events.

3.2 Methods

3.2.1 Description of Malaba River Catchment

The Malaba River catchment is a transboundary catchment shared between Uganda and Kenya. The river originates from the slopes of Mount Elgon and drains its waters into Lake Kyoga, which is located in central and mid northern Uganda (Figure 3.1). About 70 percent of the catchment is situated in the Eastern part of Uganda (618159.6N, 64877.5E) i.e. downstream and midstream sections of the catchment, while the remaining portion is situated in western Kenya (666168.4N, 79848.4E) zone 36N i.e. the upstream section. The size of the catchment is 2,232km^2. The catchment has a total of 32 sub-catchments covered with swamps originating along the tributaries. The major sub-catchments within the Malaba River catchment include the Okame, Aturukuku, Solo, Malakisi, and Lwakhakha Rivers. The catchment has a bimodal rainfall pattern with an average annual rainfall of 1,514 mm/year. The wettest and driest months are from March to April and June to October respectively, while temperatures range from 15.8 °C to 30.6 °C.

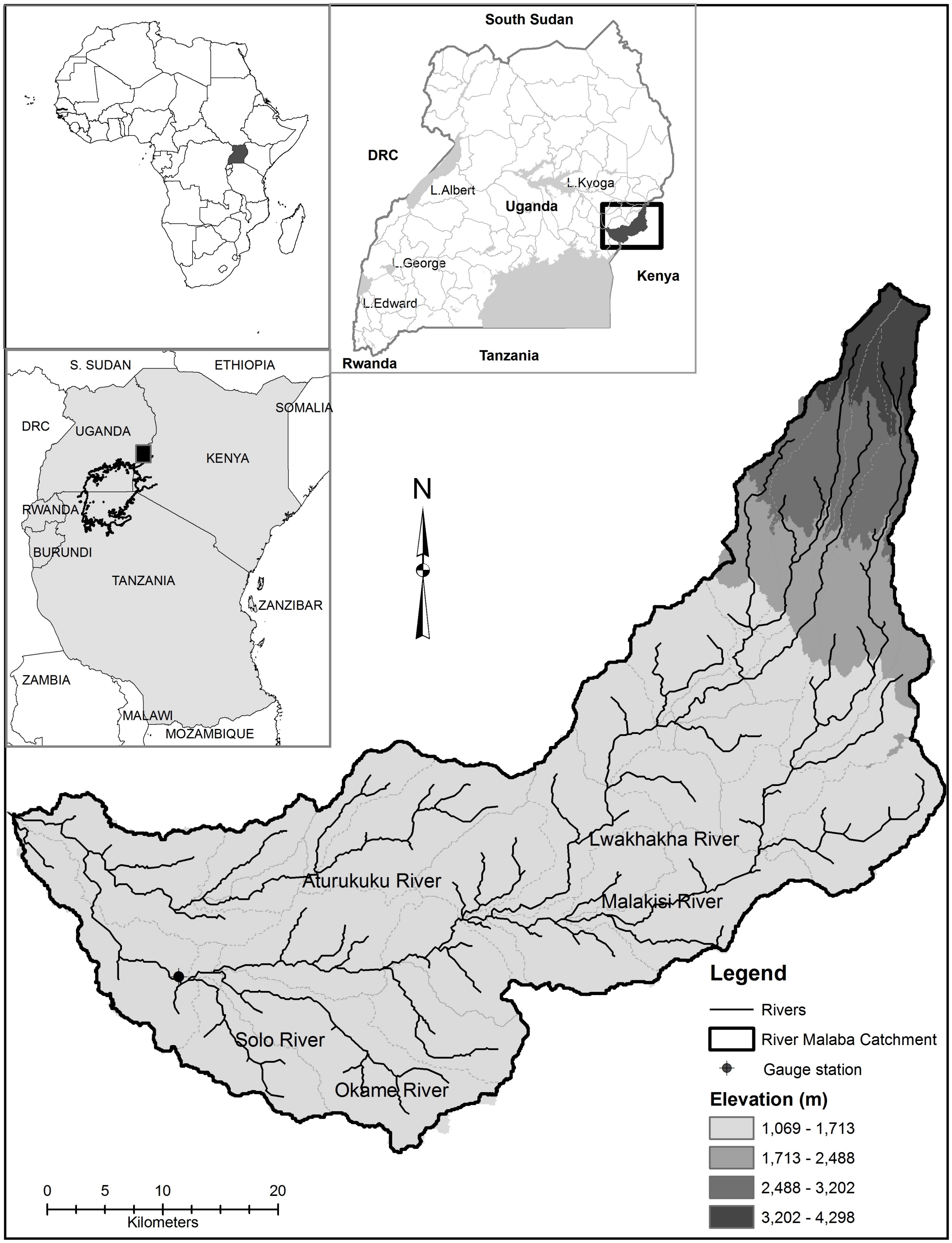

Figure 3.1: The Malaba River Catchment

3.2.2 Meteorological, streamflow and normalized difference vegetation index data

The study obtained daily time series catchment based meteorological and stream gauge data from two stations (upstream and downstream) managed by the Ministry of Water and Environment, Uganda. The obtained data were subjected to homogeneity tests (Rugumayo and Mwebaze, 2002). The considered study periods were from 1983-2011 for extreme weather events assessment and 1992-2011 for streamflow fluctuation assessment. The longer the period of data record, the more reliable the assessment or prediction of weather events (Hayes *et al.,* 1999; Wu *et al.,* 2005). The consideration for the two studied periods was attributed to the inadequacy of discharge data attributed to the effect of political turmoil from the second half of the 1970s until around 1985 (Ades and Hak, 1997).

The combined drought index (CDI) requires Normalized Difference Vegetation Index (NDVI) values as input into the index. The study obtained NDVI values from the MODIS NDVI (Terra and Aqua-MOD44 16-day) time series (250m) data from the Global Agriculture Monitoring Project (Justice *et al.,* 2002; GarcĂa-Mora *et al.,* 2012).

3.2.3 Extreme weather events assessment

The study compared two drought indices (CDI and SPI) to characterize the frequency and severity of extreme weather events in the catchment. The SPI drought index was used to quantify the precipitation deficit for multiple time scales, which reflect the effect of extreme weather events on the availability of water resources (McKee *et al.,* 1993). A long-term precipitation record is fitted to a probability distribution, which is then transformed into a normal distribution, so that the mean SPI is zero. The SPI threshold to classify drought and flood events corresponds to the cumulative distribution and moisture categories (McKee *et al.,* 1993; McKee *et al.,* 1995).

$$SPI = \frac{X_{ij} - X_{im}}{\sigma} \quad (1)$$

Where, X_{ij} is the seasonal precipitation at the i^{th} rain gauge station and j^{th} observation,X^{im}) the long–term seasonal mean andσ its standard deviation.

The SPI values were interpreted using the following scale (Table 3.1).

Standard Precipitation Index	Cumulative Density Function	Moisture category
-3.0	0.001	Extreme dry (ED)
-2.5	0.006	
-2.0	0.023	
-1.5	0.067	Severe dry (SD)
-1.0	0.159	Moderate dry (MD)
-0.5	0.309	Incipient dry (ID)
0.0	0.500	Incipient wet (IW)
0.5	0.691	
1.0	0.841	
1.5	0.933	Moderate wet (MW)
2.5	0.994	Extreme wet (EW)
3.0	0.999	

Table 3.1: Definition of Standard Precipitation Index parameter

The CDI was developed by the UN Food and Agriculture Organization (Balint *et al.*, 2011). The index integrates three individual drought indices, which include the Precipitation Drought Index (PDI), the Temperature Drought Index (TDI), and the Vegetation Drought Index (VDI) as a substitute for the Soil Moisture Drought Index (Atzberger, 2013; Enenkel *et al.*, 2013).

The equations for calculating the PDI, TDI and VDI for year 1 and time unit (dekad/month) m are given in Equations (2) to (4).

$$PDI_{i,m} = \frac{\frac{1}{IP}\sum_{j-0}^{IP-1} P^*_{i,(m-j)}}{\frac{1}{(n*IP)}\sum_{k-1}^{n}\left[\sum_{j-0}^{IP-1} NDVI^*_{(m-j),k}\right]} * \sqrt{\left[\frac{RL^{(P*)}_{m,i}}{\frac{1}{n}\sum_{k-1}^{n} RL^{(P*)}_{m,k}}\right]} \tag{2}$$

$$VDI_{i,m} = \frac{\frac{1}{IP}\sum_{j-0}^{IP-1} NDVI^*_{i,(m-j)}}{\frac{1}{(n*IP)}\sum_{k-1}^{n}\left[\sum_{j-0}^{IP-1} NDVI^*_{i,(m-j),k}\right]} * \sqrt{\left[\frac{RL^{(NDVI*)}_{m,i}}{\frac{1}{n}\sum_{k-1}^{n} RL^{(NDVI*)}_{m,k}}\right]} \tag{3}$$

$$TDI_{i,m} = \frac{\frac{1}{IP}\sum_{j-0}^{IP-1} T^*_{i,(m-j)}}{\frac{1}{(n*IP)}\sum_{k-1}^{n}\left[\sum_{j-0}^{IP-1} T^*_{i,(m-j),k}\right]} * \sqrt{\left[\frac{RL^{(T*)}_{m,i}}{\frac{1}{n}\sum_{k-1}^{n} RL^{(T*)}_{m,k}}\right]} \tag{4}$$

Where:

P^* is the modified monthly or 10–day precipitation amount,

T^* modified monthly or 10–day average temperature,

$NDVI^*$ modified monthly or 10–day average Normalized Difference Vegetation Index

IP Interest Period

RL(P) (run-length) is maximum number of successive dekads or months below long term average rainfall in the interest period

RL(T) maximum number of successive dekads or months above long term average temperature

RL (NDVI) maximum number of successive dekads or months below long term average NDVI in the IP,

n number of years with relevant data,

j summation running parameter covering the IP, and

k summation parameter covering the years when relevant data are available

The calculation of the Combined Drought Index is computed as the weighted average of the precipitation, the temperature, and the soil moisture drought indices.

$$CDI_{i,m} = w_{PDI} * PDI_{i,m} + w_{TDI} * TDI_{i,m} + w_{VDI} * VDI_{i,m} \quad (5)$$

Where;
W = is the weight of the individual drought index.

The interpretation of the Combined Drought Index is that if the CDI is greater than 1.0, it represents wetter than average, if it is below 1.0, (Balint *et al.,* 2011) it represents drier than average conditions (Table 3.2). The duration, intensity and severity of the events were identified and characterized using a run theory as demonstrated by Mishra and Singh (2010).

SCDI value	**Drought Severity**
>1.0	No drought
1.0–0.8	Mild
0.8-0.6	Moderate
0.6-0.4	Severe
<0.4	Extreme

Table 3.2: Interpretation of Combined Drought Index

3.2.4 Relationship between extreme weather events and streamflow

The IHACRES model (Identification of unit hydrographs and component flows from rainfall, evaporation and streamflow data) was used to characterise the relationship between extreme weather events and streamflow (Croke *et al.,* 2005). The IHACRES model consists of two modules: a non-linear loss module to convert rainfall to excess rainfall, and a linear module to convert effective rainfall to streamflow. The non-linear loss module uses temperature and rainfall to estimate a relative catchment moisture store index (Post *et al.,* 1996). The theoretical description, assumptions, capabilities and advantages, of using the IHACRES model are described in detail by Evans and Jakeman (1998); Schreider *et al.* (2000); and Dye and Croke (2003). To determine the performance of the model, the daily time series of streamflow, temperature and rainfall data were synthesized within the model for the period between 1992 and 2011. The best sections of the streamflow and rainfall data were selected for calibration based on the reliability and quality of available data as described by Hansen *et al.,* (1996). The quality of the calibration and validation was finally judged by both visual and statistical comparisons between simulated and observed flows. The performance of the model was evaluated following the Nash and Sutcliffe (1970) procedure. The Nash-Sutcliffe Efficiency (NSE) criterion contains information on reported values; and reflects the overall fit of a hydrograph (Moriasi *et al.,* 2007).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{N} (Yi^{obs} - Yi^{sim})^2}{\sum_{i=1}^{N} (Yi^{obs} - Yi^{mean})^2} \right]$$

Where Yi^{obs} is the ith observation for the constituent being evaluated, $Yi^{\mathrm{sim}}$is the ith simulated value for the constituent being evaluated; and Yi^{mean} is the mean of the observed data for the constituent being evaluated; and n is the total number of observations.

3.2.5 Socio-economic survey

The frequency and severity of extreme weather events in the catchment were also examined through a survey of 40 key informant interviews. The officials from the Local and National Government Natural Resources Management Departments (Tororo and Busia Districts), Ministry of Disaster Preparedness and Management and Uganda Red Cross Society constituted the respondents' list. The selected respondents were more knowledgeable about the re-occurrence and occurrence of extreme events in the catchment.

3.3 Results

3.3.1 Extreme weather events

The SPI index showed that the drought events were mainly experienced in years 1993 (-2.52), 1990 (-1.26), 2004 (-1.21) and 1986 (-1.01); whereas the wettest periods were experienced in years; 2006 (2.37), 1997 (1.80), 2008 (1.55), and 1988 (0.90) (Figure 3.2). The SPI results indicated that a greater than median precipitation was recorded in the 1995-1999 and 2006-2008 periods, while a less than median precipitation was recorded in 1999-2004, 1992-1995, and 1984-1999 in the studied period (Figure 3.2).

The CDI showed that the catchment experienced extreme drought events in 2006 (0.38) and 2009 (0.41), while severe drought events occurred in 1998 (0.48), 2011 and 1993 (0.51), 2005 (0.52), 2009 (0.54), 1990 (0.58) and 2008 (0.59) (Figure 3.3). Severe flood events occurred in 1990 (2.2), 1998 (2.14), 1997 (2.02), 1985, 2003 and 2010 (1.7) (Figure 3.3). Comparatively, the CDI showed that the driest years were 2005 and 2006, while 1997-1998 were the wettest years (Table 3.3). At least more than two multi-year drought events were recorded by both the CDI and SPI indices in the studied period (1983-2011).

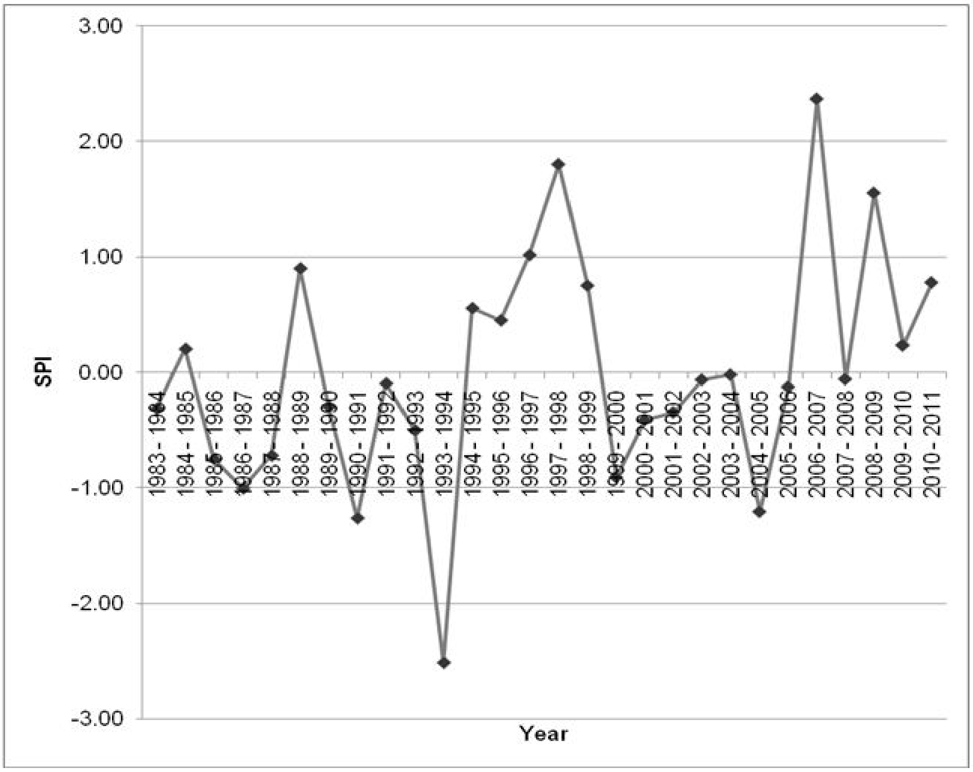

Figure 3.2: Standardized Precipitation Index (1983-2011) period

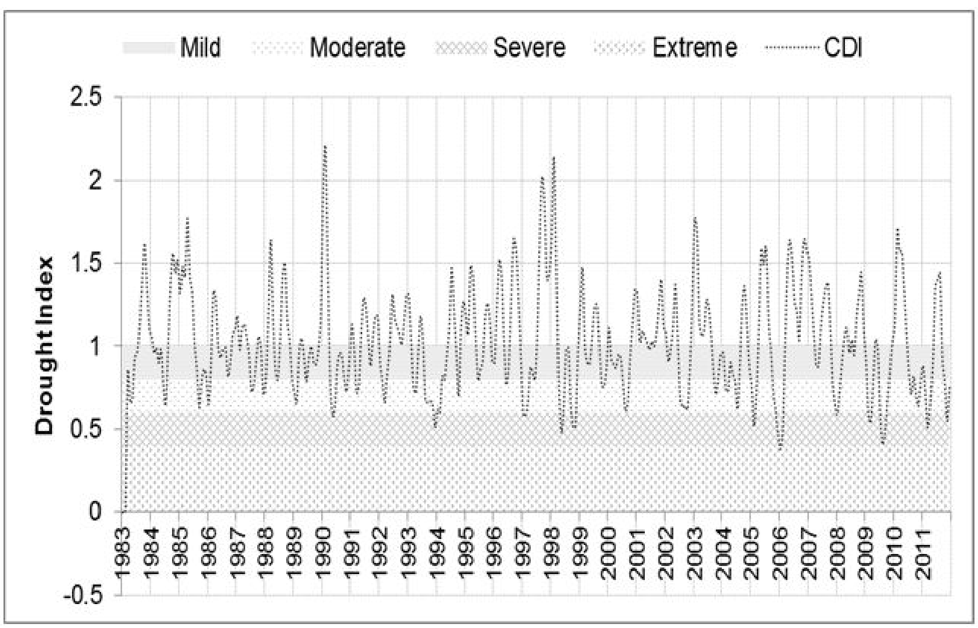

Figure 3.3: The Combined Drought Index (1983-2011)

Drought and flood events characteristics	SPI		CDI	
	Drought	**Floods**	**Drought**	**Floods**
Longest duration	1999–2004	1995–1999	1993–1994	1984–1985
Highest intensity	1992–1995	2006–2008	2005–2006	1990
Highest severity	1984–1999	1995–1999	2005–2006	1997–1998
Threshold of severity	−2.52	2.37	0.38	2.2

Table 3.3: The flood and drought events characteristics

3.3.2 Extreme weather events and streamflow

The model showed that the catchment experienced a severe drought in 2007 in the first quarter of the year unlike in the last quarter (October to December) where it experienced frequent floods. The IHACRES model predicted well peak flows than drought events. Overall, the IHACRES model performed slightly better in the simulation period (R^2= 0.8) than in calibration (R^2= 0.7) period for the two decadal periods in examining the relationship between extreme weather events in relation to streamflow.

The NSE of 0.8 showed that the performance of the model was satisfactory (Figure 3.4), much as the model overestimated the discharge in the dry periods 1996, 2005, 2006 and 2011. The performance of IHACRES model comparatively corresponded with the results obtained from the SPI and CDI drought indices, particularly the severity of drought that took place in 2005 and the floods in 1997 (Table 3.4).

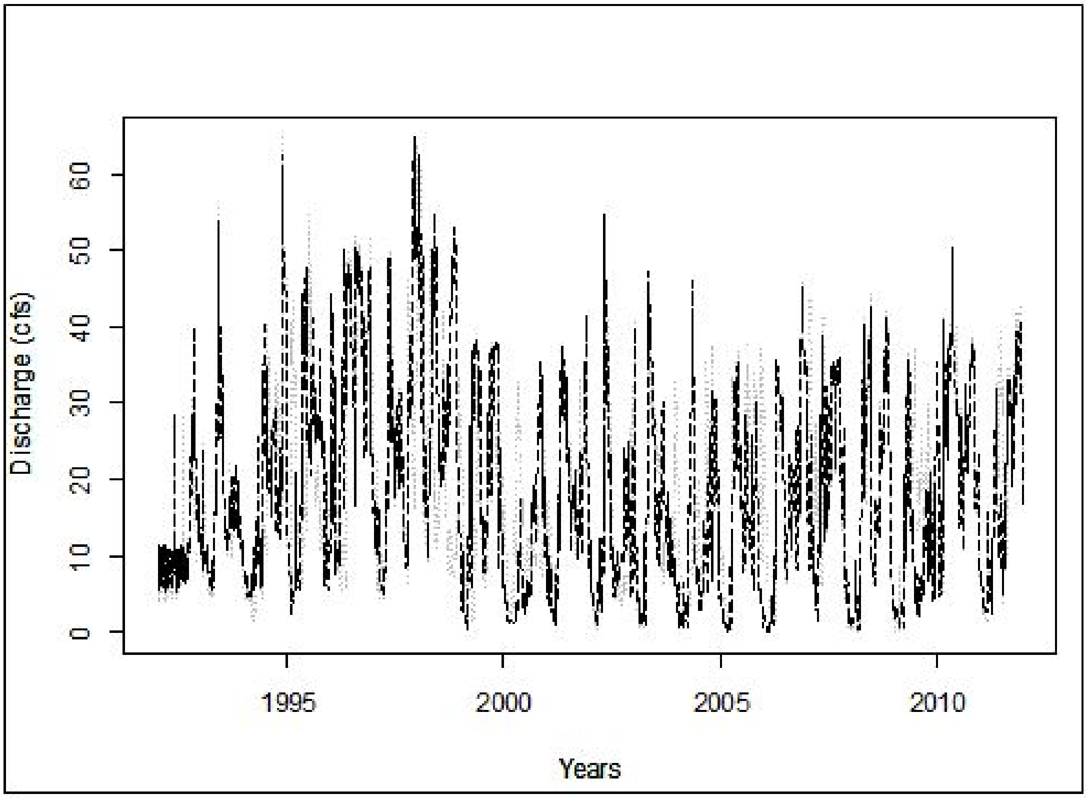

Figure 3.4: Simulated and observed discharge values for 1992–2011 period

Events	IHACRES(years)	SPI(years)	CDI(years)	Severity)
Drought	2007	1993	2006	Extremely dry
	2006	1991	2009	Dry
	2008	2005	1998	Moderately dry
	2005	1987	2005	Less dryness
Flood	1996	1997	1990	Extremely dry
	1997	2007	1997	Dry
	2010	2009	1985	Moderately dry
	2011	1989	2003	Less dryness

Table 3.4: Comparisons between the SPI, CDI and IHACRES model

3.4 Discussion

The study shows that the frequency of extreme events (droughts and floods) over the catchment has reduced. The occurrence of these events comparatively corresponded with the peak streamflow basing on the observed streamflow data and recorded extreme weather events periods in the catchment. With regard to drought and flood events, the study showed that their frequency has reduced from a 4-10 year period to a 1-3 year period. By identifying the frequency of these periods' events on a long time scale (12 months), this study has been able to provide evidence that a local level analysis yields greater and detailed results. This finding is in contrast to the findings of Vicente-Serrano *et al.* (2012) who based their work with the SPEI over Africa. They concluded that in East Africa at a longer time-scale of 12 to 24 months, droughts were less frequent than in the shorter time-scale (3 to 6 months).

The drought events identified in 1987, 1998, 1999, 2002, 2005 and 2008 also coincided with the La-Nina events that were recorded in the country and, which had devastating effects (Kagawa, 2009). The predicted flood events occurred in the year 1997, 2007, 2010 and 2011. These flood events also coincided with the general floods that hit the nation during this time. The flood events were attributed to the El-Nino Southern Oscillation and a response to the Indian Ocean Dipole. These floods contrast with conditions for the larger part of East Africa that recorded drought in 2010 and 2011 (Russell and Johnson, 2005). The occurrence of flood events showed a probable change in the pattern of rainfall received in the catchment. This study may not yet arrive at a full interpretation of such changes, although other scholars have already suggested that these extreme events are on the rise (Kagawa, 2009).

The drought indices have shown differing identification of drought and flood periods with minimal convergence. It was also observed that the intensity of extreme events varied depending on the drought indices. The CDI was a better predictor of drought events (2005-2006) than the SPI, which was better for flood events (2006, 1997 and 2008).

The strength of each of these methods lies in its original design for a specific purpose (Ntale and Gan, 2003; Balint *et al.,* 2011); the CDI incorporates more climatic variables (temperature, rainfall and NDVI) than the SPI index. The performance of the IHACRES model corresponded with the results obtained from the SPI and CDI drought indices, especially the severity of the drought event that occurred in 2005 and floods in 1997. The modelled peak and low flow periods corresponded with the recorded extreme weather events.

The model estimated that the peak flows were more similar to the observed discharge during the flood events than in the dry periods. This is similar to the findings of Singh (1997) who observed that the shape, timing and peak flow of the streamflow hydrograph are significantly influenced by the spatial and temporal variability in rainfall and catchment characteristics because the hydrological responses are closely linked to storm dynamics. The model results also showed that the catchment experienced severe drought events in the first quarter of the year, and many floods from October to December. This is in agreement with the findings of Russell and Johnson (2005), who noted that climatic projections for Uganda showed an increasing trend of heavy rainfall events, particularly in the last quarter of the year in October, November and December especially in the 21^{st} Century.

The IHACRES model slightly overestimated streamflow in the dry years (1996, 2005, 2006 and 2011). This could be attributed to a much higher discharge than usual and therefore the measured discharge data might not have been measured accurately in under normal circumstances (Marshall *et al.,* 2012). The frequency and severity of extreme weather events in relation to streamflow could also be attributed to an intensification of human activities, such as conversion of natural land cover into agricultural fields (Zhang *et al.,* 2011) that resulted into increased surface rainfall-runoff through climate variability through floods. In addition, a high variation of streamflow in response to flood events in the Malaba River could be attributed to the elongated shape of the catchment that causes a reduction in the travel time of surface runoff to the main channel and a high number of tributaries.

3.5 Conclusion

The catchment is currently experiencing frequent recurrence of drought and flood events with high intensity. This corresponds with the high streamflow variations compared to the 1980s. The CDI was a better predictor of drought events than the SPI, which was better for flood events that were observed in the catchment. The performance of the IHACRES model corresponded with the results obtained from the SPI and CDI drought indices, especially during the severity of drought and flood events recorded in the catchment. The modelled peak and low flow periods corresponded with the recorded extreme weather events. However, to improve on the accuracy of extreme event predictions there is a need for data collectors to follow the data quality control mechanisms for stream flow and meteorological data collection. This will avoid reliance on limited and inconsistent data. The aim should be to secure scientific information, and not to rely on speculation. Prediction of extreme weather events, streamflow, and climate change must become more reliable.

This chapter focused on assessing the effect of extreme weather events on the streamflow. This information is important in understanding the hydrological responses of the Malaba River catchment to extreme weather events in the face of increasing threats of natural land cover conversions into crop growing. The subsequent chapter four focuses on the effect of land use and cover change on the soil properties and their implications for the rainfall-runoff generation and volume.

Chapter 4

Determining and estimating the effect of land use and cover change on the soil properties and their implications for the rainfall-runoff generation and volume in the Malaba River catchment, Eastern Uganda

Abstract

Land use and cover change may affect the soil and precipitation, which are important factors in the rainfall-runoff generation that ends up in the river channel and becomes streamflow. This study investigated the susceptibility of the soil to rainfall-runoff generation and volume from different land uses and cover types. These were assessed through carrying out soil infiltration experiments and curve number model estimation of runoff volume. The results indicated that the land use and cover types had a significant effect on the content of nitrogen, sand, phosphorus and organic matter ($P<0.05$) than on the percentage of clay and silt in the 0-30cm soil depth. The forest cover, cotton and beans land use types exhibited the highest rates of infiltration (>40 mm/hr.), than in the rice and woodland. The agricultural land use (crop growing) had relatively high rates of rainfall-runoff generation than the forest and bushlands cover types. The low rates of saturated hydraulic conductivity from the agricultural land use (crop growing) reflected an increase in the rainfall-runoff generation which translated into an increase in the streamflow. The curve-number model estimated a comparatively higher rainfall runoff volume generated from agricultural land use (crop growing) (71,740 m^3) than in the bushlands and thickets (42,872 m^3) from a single rainfall storm followed by the tropical forest.

Keywords: Land use, cover, rainfall-runoff, infiltration, Malaba, Curve-Number

4.1 Introduction

Land use and cover change may affect the regional and local scale water resources (Huisman *et al.,* 2004; Shi *et al.,* 2007; Turyahabwe *et al.,* 2013) by influencing changes in rainfall-runoff components and the climate (Schulze, 2000; Hernandez *et al.,* 2000; Kim *et al.,* 2002). This change is driven by the intense human utilization of land resources (Lorup *et al.,* 1998; Bronstert *et al.,* 2002; Barasa *et al.,* 2011) to provide food, fibre, water, and shelter to more than six billion people worldwide (Foley *et al.,* 2005). This results into an increase in the magnitude of rainfall-runoff volume and peak discharge (Muhammad *et al.,* 2011; Fox *et al.,* 2012).

The effects of land use and cover change on hydrological responses are more prominent in the tropical regions, and their contribution is substantially larger than that of climate change. These changes have increased the global runoff by 0.08 $mm/year^2$, and accounts for ≈ 50 percent of the reconstructed global runoff trend over the last century (Piao *et al.,* 2007). Therefore, investigating the effect of land use and cover on the soil susceptibility to rainfall-runoff generation and volume is a prerequisite to understanding hydrological responses in a catchment (Niehoff, 2002; Pfister, 2004). This is because hydrological responses are dependent on the surface and soil physio-chemical properties (Kirkby *et al.,* 2005) such as antecedent soil moisture (Nutchanart and Wisuwat, 2011), organic matter, soil texture, macro-pores, roots or micro-topography channelling water movement (Braud *et al.,* 2001; Hundecha and Bárdossy, 2004).

Little is known so far if there is a well-defined quantitative relationship between the land use and cover change and rainfall-runoff generation at a catchment scale (Hundecha and Bárdossy, 2004 Samaniego and Bardossy, 2006; Wei *et al.,* 2007). Much as quantifying this relationship using soil infiltration experiments is limited in the tropical region (Giertz and DiekkrĂźger, 2003). This study bridges this information because it is important to gain an understanding of what these specific effects are. Therefore, the present study sought to establish the characteristics of the soil under different land use and cover types and their effect on the surface rainfall-runoff generation that later translates into streamflow in the catchment. It is against this background that this study critically examined the effect of land use and cover on soil properties and their implications for the rainfall-runoff generation and volume in the Malaba River catchment.

4.2 Materials and Methods

4.2.1 Description of the Malaba River Catchment

The catchment of Malaba River lies in the continuously humid non-tropical - cyclone sub-region in terms of rainfall. This sub-region is found within a relatively narrow band at 3°N - 5°S latitude. The catchment is a transboundary in nature because it is shared between Uganda and Kenya (Figure 4.1). The river originates from the slopes of Mount Elgon and drains into Lake Kyoga, which is located in the central and mid northern part of Uganda (Figure 4.1). Seventy percent of the downstream and midstream sections are located in the eastern region of Uganda (618159.6N, 64877.5E), while the remaining portion (the upstream section) is situated in western Kenya (666168.4N, 79848.4E) zone 36N. The extent of the catchment is 2,232 km^2. Mt. Elgon is also the main source of Lwakhakha, and Malakisi rivers. These tributaries discharge into Lake Kyoga at an elevation of 950 meters ASL. The minor tributaries include Rivers Solo, Aturukuku, and Okame. The catchment experiences a bimodal rainfall pattern with an average annual rainfall of 1,514 mm/year.

The major socioeconomic activity is subsistence farming. In terms of land cover, the catchment is endowed with diverse types of natural and plantation vegetation, which ranges from the high altitudinal coniferous vegetation, tropical high forests through swamps to savannahs. The major soil types are sandy-loams and clays. The sandy-loams are found in the upland areas, while the clays in the valleys. These soil types have a little difference in their defining soil horizons. The major soil types fall mainly under two soil catena groups, which are the Petric plinthosols, and Gleysols. The remaining soil types are under Lixic ferrasols, Acric ferrasols and Nitisols. The soil catena groups can be distinguished easily because they represent earlier stages of the weathering processes (NEMA, 1997).

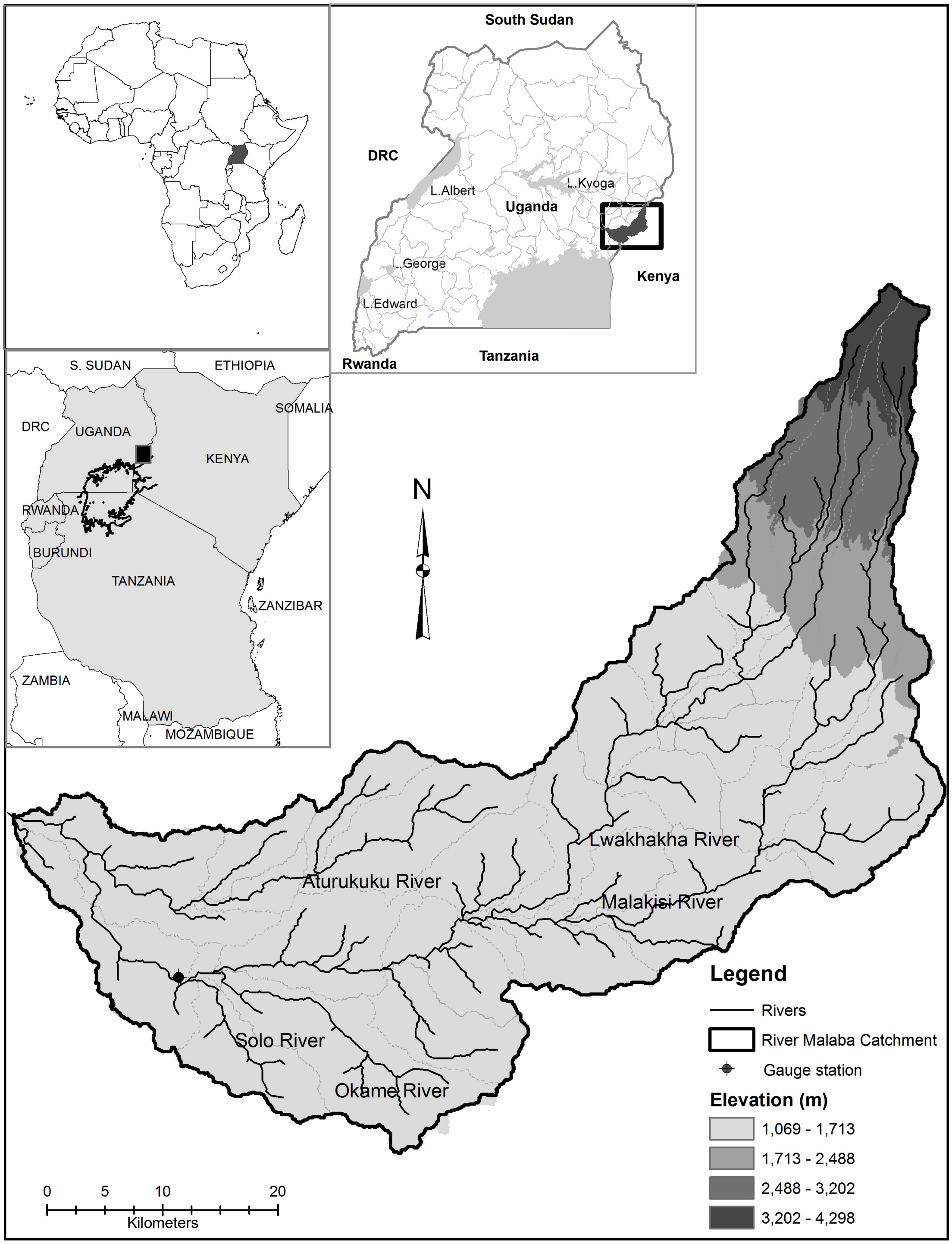

Figure 4.1: The Malaba River Catchment

4.2.2 Study approach

Soil sampling was carried out from the Petric plinthosol, and Gleysol soil types to determine the effect of land use and cover change on the soil properties susceptibility to rainfall-runoff generation. This was assessed through soil sampling and use of soil infiltration experiments. The two soil groups had a diversity of land use and cover options, which meant that they were more prone to both natural and human disturbances. The curve number model was applied in this study to estimate the rainfall runoff volume because of its comprehensive inclusiveness of components that influence land use and cover components in the catchment.

4.2.3 Susceptibility of the soil to runoff

4.2.3.1 Soil characteristics

The study laid out field plots (50 x 50m) that were measured 100m away from the river channel where soil composites were randomly sampled from the representative land use and cover types (agriculture, tropical forest, regenerating forest, bushlands, tree plantation, and wetland) following a zigzag method. Soil sampling was carried out at two soil depths i.e. 0-15cm and 15-30cm. The collected soil samples were analysed in the laboratory following Okalebo *et al.* (2002) laboratory methods for soil analysis. A one-way analysis of variance (ANOVA) was performed on the analysed samples to test if land use/cover types and soil depth had an effect on the soil properties ($P<0.05$).

4.2.3.2 Soil infiltration

A series of double ring soil infiltration experiments were conducted from representative land use and cover types situated from the prominent hill slopes to the valleys. These experiments were adopted because water infiltration is an important component of the catchment water balance. The double ring technique was chosen because it minimized the slacking effect and the effect of lateral water flow (Achouri and Gifford, 1984; Bamutaze, 2010). The infiltration rate was assessed by observing the decreasing water level inside the inner ring. Water in the outer ring was kept at approximately the same level as in the inner ring to prevent lateral flow and promote vertical water movement in the soil (Moroke *et al.*, 2009).

The experiments were conducted on the representative land use and cover types, that were situated from the two soil catena groups (Petric plinthosols and Gleysols). Under the Petric plinthosol soil type, agricultural land use comprising of cassava, maize, cotton, sorghum and land cover comprising of forest, bushlands, and tree plantation were sampled. From the Gleysols - rice, bushlands and woodland land use/cover types were sampled. The collected soil samples were analysed in the laboratory for saturated hydraulic conductivity using the constant head method. The soil hydraulic conductivity rates were defined and classified in accordance with the United States Department of Agriculture (1983) rating scheme.

4.2.4 Estimation of runoff volume

The U.S. Soil Conservation Service, (1972) curve number model was adopted by this study to estimate rainfall-runoff volume. The model accounts for the factors that affected runoff, such as soil type, land use, surface and antecedent moisture condition (Ponce and Hawkins, 1996; Soulis *et al.*, 2009; Xiao, 2011). The runoff equation was expressed as:

$$Q = \frac{(P - O.2S)^2}{(P + 0.8S)}, \quad P0.2S \tag{1}$$

Q = 0 , P<0.2S

Where, Q is direct runoff (1000/C)-10 in inches, P is storm rainfall, and S is potential maximum retention or infiltration. Equation (1), S is expressed in the form of a dimensionless runoff curve number (CN):

$$S = \frac{25400}{CN} - 254$$

in mm, SI units

Where, CN represents the runoff (mm) potential of the land cover soil-complex governed by soil property, cover type and the hydrologic condition of the soil surface. The runoff volume was determined when the area was multiplied by runoff depth.

The allocated curve number values for the different land use and cover types were as follows; Gleysols had a CN range from 0 to 1, while those under the Petric plinthosols ranged from 73 to 79. However, the highest curve number values were allocated to the degraded forest and built up areas (Figure 4.2).

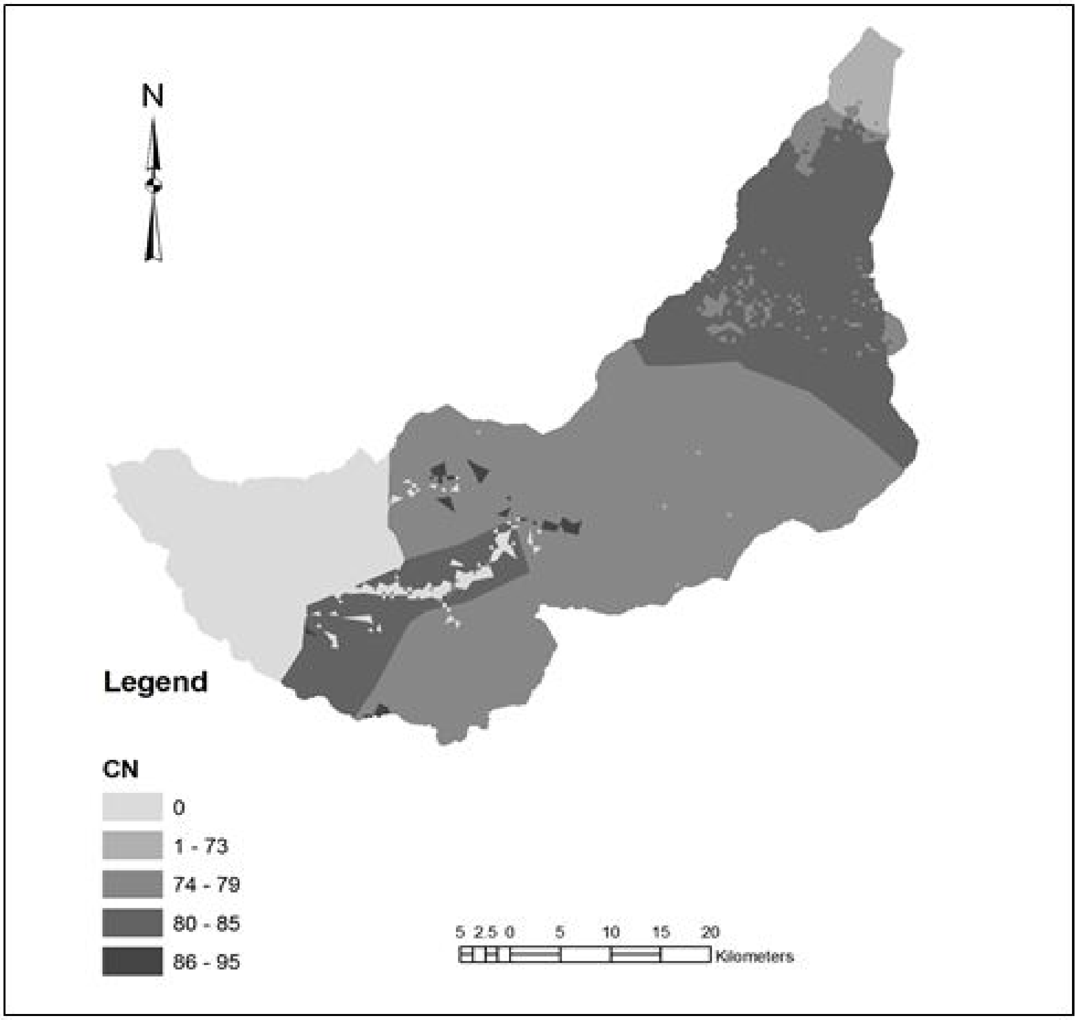

Figure 4.2: Curve number ranges

4.3 Results

4.3.1 Effect of land use and cover change on the soil properties

4.3.1.1 Soil characteristics

The soil physio-chemical properties for the representative land use and cover types are summarized in Table 4.1. The effects of land use and cover change varied with soil depth and the representative land use and cover types. From the sampled land use and cover types, the most affected soil properties were the clay fraction and phosphorus at the 0-15 cm soil layer (P<0.05); while nitrogen and organic matter content at the 10-30 cm soil layer (Table 4.1).

Properties	**Soil Depth**	**Wetland**	**Agriculture**	**Forest**	**Bushlands**	**Tree Plantation**	**Forest (Reg)**	P<0.05
Nitrogen (%)	0–15cm	0.292	0.15	0.225	0.183	0.217	0.1	ns
	15–30cm	0.008	0.15	0.333	0.075	0.125	0.233	**
Phosphorus	0–15cm	9.91	1.224	6.063	4.722	6.879	0.915	**
(ppm)	15–30cm	0.057	5.48	12.5	1.144	1.201	4.37	ns
Bulk density								
(g/cm^3)	0–15cm	0.269	0.186	0.615	0.359	0.314	0.301	ns
	15–30cm	0.276	0.192	0.667	0.051	0.167	0.176	ns
Organic								
Matter(%)	0–15cm	5.985	3.214	4.101	3.547	4.323	1.271	ns
	15–30cm	2.882	4.323	7.98	1.441	2.882	4.655	**
Sand (%)	0–15cm	50	36	42	34	42	80	ns
	15–30cm	58	48	50	82	68	52	ns
Clay (%)	0–15cm	21	32	27	31	28	13	**
	15–30cm	16	28	25	11	15	27	ns
Silt (%)	0–15cm	29	32	31	35	30	7	ns
	15–30cm	26	24	25	7	17	21	ns

Table 4.1: The mean values of soil physio–chemical properties from the sampled land use and cover types

ns: not significant; ** significant (P<0.05.; Reg. (Tropical Forest Regeneration)

4.3.1.2 Susceptibility of the soil to runoff generation

Soil texture can show the behaviour of soils in terms of their chemical and physical properties. The percentage of sand varied across the sampled representative land use and cover types with soil depth. The percentage of sand was relatively higher in the subsoil layer than for silt and clay. In regard to the soil particle size instability, the fractions of silt and sand showed that they were more susceptible to detachment in the rainfall-runoff generation than the clay fractions.

4.3.1.3 Soil infiltration

Figure 4.3 shows the rates of measured soil infiltration from the sampled representative land use and cover types. The rates of soil infiltration varied across the sampled representative land use and cover types, and soil catena groups. The observed rates of soil infiltration were relatively higher in the Petric plinthosol soil type than in the Gleysols. The tropical forest land cover, cotton and beans land use types showed higher rates of soil infiltration than the observations made under the rice and woodland land use and cover options. Generally, the observed rates of soil infiltration were higher in the agricultural land uses than from the sampled land cover types in the catchment.

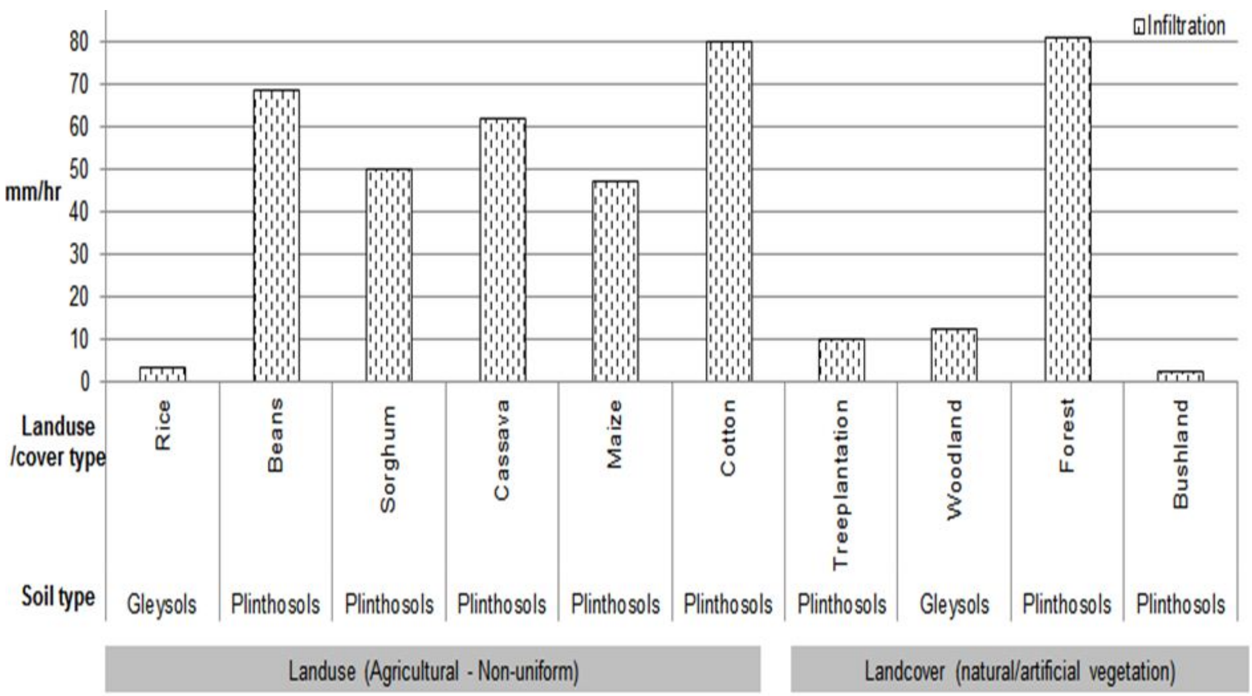

Figure 4.3: Rates of soil infiltration from the sampled landuse and cover options

4.3.1.4 Soil hydraulic conductivity

The soil hydraulic conductivity (k_{sat}) plays a critical part in the runoff generation process because it controls the lateral flow of rainfall in the soil profiles. The agricultural land use types (beans and maize) had moderate rates of soil conductivity in the topsoil layer compared to the land cover types (forest, bushlands and thickets, woodland). However, the Gleysols had a lower saturated hydraulic conductivity than the Petric plinthosol soil type. The low rates of k_{sat} in the agricultural land use types (crop growing), showed a characteristic of Petric plinthosol type (Table 4.2). The one-way ANOVA procedure was implemented to test the significance of land use and depth on the k_{sat}. The results indicated that the effect of land use and cover types were more significant ($P<0.01$) on k_{sat}, than in relation to the soil depth ($P>0.65$).

Soil type	Land use/ cover types	Soil depth (cm)	k_{sat}(mm/day)	Rating
Gleysols	Rice	0–15	243	Low
		15–30	19	Very low
	Cotton	0–15	163.6	Low
		15–30	312.2	Low
	Beans	0–15	1338.4	Moderate
		15–30	96.3	Very low
Petric plinthosols	Sorghum	0–15	393.2	Low
		15–30	327	Low
	Cassava	0–15	224.4	Very low
		15–30	204	Low
	Maize	0–15	824.6	Moderate
		15–30	2335.8	High
	Bush land	0–15	171.4	Very low
Petric plinthosols		15–30	14.7	Very low
	Tree Plantation	0–15	140.7	Very low
		15–30	354	Low
	Forest	0–15	3726.3	Very low
		15–30	1822.1	High
Gleysols	Woodland	0–15	30.4	Very low
		15–30	32.5	Very low

Table 4.2: The saturated hydraulic conductivity from the sampled land use and cover types

4.3.1.5 Estimation of runoff volume

The SCS CN model estimated that the highest rainfall-runoff volume was generated from the agricultural land use followed by bushlands and thickets land cover types (Table 4.3). The high rate of runoff volume could be attributed to the high rate of natural land cover conversion to crop growing. This is accompanied by poor farming practices such as bush burning, selective depletion of forest cover for charcoal burning and firewood extraction among others. The predicted model results also showed a strong correlation between the CN values and the depth of rainfall storms events experienced in the catchment.

Period	**2013**
Land use/cover types	**Runoff volume (cubic metres)**
Woodland	8,460
Tropical Forest (Fully stocked)	12,827
Tropical Forest (Regeneration)	11,952
Bushlands and thickets	42,872
Agriculture (Non Uniform)	71,740
Wetland (Permanent)	372
Built up (Towns)	659
Open water (Swamp)	2

Table 4.3: Predicted runoff volumes from the land use and cover types

4.4 Discussion

This study revealed that the sampled representative land use and cover types in the catchment had a moderate effect on the soil properties and rainfall-runoff generation. Thus, the land uses and cover options under the Gleysols contributed a significant amount of runoff that ended up as streamflow. However, this impact greatly depended on the amount of precipitation received in the catchment. This finding was also observed by Niehoff *et al.,* (2002) who argued that the influence of land-use conditions on storm-runoff generation depends greatly on the rainfall event characteristics and on the related spatial scale. The impact was more significant from the agricultural land use (crop growing) than from the land cover options. The cultivated areas (beans, maize, sorghum, and cassava) were more susceptible to generate intermediate amounts of rainfall-runoff, especially under an average rainfall higher than 1,000 mm per year. The continuous cultivation practices without external inputs, and encroachment on the marginal areas for more fertile land increased the susceptibility of the soil to runoff through the exposure of the soil to the rainfall-runoff agents. Rockstrom (2000) also found out that the practices exist because over 95 percent of the land used for food production is based on rain-fed agriculture and it's prone to rainfall-runoff in the Eastern Africa.

The poor cultivation practices were also responsible for the low availability of organic matter content in the soil. This effect was also noted by Lal (1985) that soils with low levels of organic matter content, and those containing predominantly low-activity clays are more susceptible to rainfall-runoff generation. This was also observed by Ikerra *et al.* (1999), Borbor-Cordova *et al.* (2006) and Barasa *et al.* (2010) who noted that the agricultural land management practices in the tropical catchments have more direct effects on the content of nitrogen, phosphorous, hydraulic conductivity and organic matter. However, the content of soil organic matter in the Malaba catchment was above the 3.0 percent critical value (Okalebo *et al.*, 2002), except for the tropical forest regeneration, where the content of organic matter was noted to be below the critical value - a phenomenon, which was attributed to charcoal burning activities. The implications for the rainfall-runoff generation were ought to be reflected in the increased rates of streamflow.

This study also shows that it is possible to estimate the rainfall-runoff generation using soil infiltration experiments and curve number method. It is also important to note that the generation of overland flow can be distinguished through saturation excess overland flow and the infiltration excess overland flow. The variation in soil texture explains the possibilities of this saturation excess. The infiltration excess was evident in the Gleysol soil type that showed a higher groundwater level. The filtration results of this study demonstrated a characteristic of loamy sand soils, which were often above 25 mm/hr. (Figure 4.3). This is also in agreement with the findings of Jansson (1982) who noted that soil filtration is a function of soil texture; and the loamy soils normally have a percolation rate of approximately 25.4 - 50.8 mm/h.

The observed rates of soil infiltration were higher in the agricultural land use (crop growing) than from the sampled land cover types in the catchment. This is also in regard with the findings of Giertz and DiekkrĂźger (2003) who reported higher rates of overland flow from the agricultural land use (crop growing) in the tropical regions. However, the high rate of soil infiltration observed in the forest land cover was attributed to the high density of root network and surface little at the top and subsoil layers. This rate was attributed to bio-turbation, which promotes non-structural macro-porosity. This effect has also been reported by Lal (1988) and Sobieraj *et al.* (2002) in the tropical rainforests. This study also notes that soil depth is not the most important parameter, which has to be considered in studying rainfall-runoff generation.

The SCS CN model estimated a higher rate of rainfall-runoff volume generated from the agricultural land use (crop growing) than in the natural land cover types. The results could be supported by poor farming methods that are destabilizing the top soil surface and properties. The estimated low runoff volume from the natural land cover options could be attributed to the effect of evapotranspiration. However, the estimated runoff volume in the catchment needs to be validated with the field measurements.

4.5 Conclusion

The forest ground cover, cotton and beans land use types exhibited higher rates of soil infiltration thus increased streamflow than in the rice and woodland. The agricultural land use (crop growing) had a high rate of rainfall-runoff generation than areas, which were under forest, and bushlands and thickets. The Curve-Number model estimated a comparatively higher runoff volume generated from the agricultural land use (crop growing) and bushlands and thickets than from the tropical forest. Therefore, assessing this impact in relation to rainfall-runoff generation is important in understanding the soil dynamics that contribute to the increase in the streamflow in the event of precipitation.

This chapter focused on the effect of land use and cover types on the soil physio-chemical properties and their implications for the rainfall-runoff generation and volume in the catchment. The next chapter assesses the extent and effect of gold mining land use on sediment loading and their implications on the variation of streamflow of the Okame River micro-catchment. Examining this impact at a micro-catchment scale can help identify the relative hydrological effects of a specific land use (gold mining) on sediment concentration in relation to the variation on the streamflow than if assessed at a broader catchment scale.

Chapter 5

Assessing the extent and effect of gold mining land use on sediment loading and their implications for the variation in streamflow in the Okame River Micro-catchment, Eastern Uganda

Abstract

Monitoring the spatial distribution and assessing the effect of gold mining activities on sediment loading/concentration is crucial in the planning and management of water, land and mineral resources in the tropical region. The extent of gold mining land use was monitored with the use of TerraSAR-X (2008) and Landsat TM/ETM+ (2013) images. Water samples and river bed deposit sediments were collected on a monthly basis to assess the effect of sediment concentrations on the streamflow. The study showed that the extent of gold mining activities increased from 4.5sq.km in 2008 to 19.9sq.km in 2013. Human-induced sediment loading through gold-stone washing in streams had a high effect on the concentration of suspended sediments and streamflow than sediments from rainfall-runoff from the sampled streams. The largest stream contributors of human-induced sediments were Rivers Nankuke (130.6kg/annum), Omanyi (70.6kg/annum), and Nabewo (66.8kg/annum) to the Malaba River. The most predominant bed deposits that dominated the river channel beds from the sampled streams were fine sand (0.25 mm) and fine gravel (4 mm). Sediment concentrations are responsible for the reduced stream water levels, modification of streamflow course, and migration of river channels and colonization of stream-channel by riparian vegetation.

Keywords: Sediments, Streamflow, TerraSAR-X, Landuse, gold-mining, Okame-catchment

5.1 Introduction

Mining activities may degrade intact ecosystems worldwide such as water bodies, land, vegetation, and wetlands among others (Van-Straaten, 2000; Bowell, 2003; Castendyk and Webster-Brown, 2007; Mpamba *et al.,* 2008). This degradation is responsible for the destruction and deformation of the earth's surface (Castro and Moore, 2000; Gao *et al.,* 2007). It affects the landscape's aesthetic value through the abandonment of mined pits, tailings and water impoundments; (Ghose, 2003; Antwi *et al.,* 2008) and, colonization of river banks by plants due to increased sediment loading (Malm *et al.,* 1990; Hilson, 2001; Machiwa, 2003; Xu, 2007).

The effects of mining have a far much higher impact on water resources than other components of the environment such as the change in precipitation (Chakrapani, 2005; Liquete *et al.,* 2009; Verstraeten *et al.,* 2009; Qiang *et al.,* 2011). These effects on the local water resources can be subdivided into two major groups those affecting the availability of water in the area (quantitative aspect) and those, which have an impact on the quality of the available water (pollution aspect) (Coetzee, 2004; Fang and Yang, 2010). Both the quantitative and qualitative impacts of mining activities on the water resources can result into increased flooding, decreased reservoir storage capacity, degradation of aquatic ecosystems and life; (Bronsdon and Naden, 2000; Reid and Trustrum, 2002; Achite and Ouillon, 2007; Gao, 2008) and migration of river channels (Hume and McGlone, 1986; Singer and Dunne, 2001; Stubblefield *et al.,* 2005; Wang *et al.,* 2006). However, an increase in sediment loading in rivers or lakes plays an important role in the transportation of nutrients and pollutants (Milliman and Syvitski, 1992; Steegen *et al.,* 2000). In addition, the information on the weight and grain size of sediments is of increasing interest to those concerned with sediment transport and related problems (Xu, 2007).

In the developing countries such as Uganda, Kenya etc, nearly all the artisanal gold mining activities are unlicensed, while a few are licensed. A considerable section of local communities are engaged in unlicensed mining activities as a source of livelihood diversification from subsistence agriculture and participation in small-scale businesses (Mutagwaba, 1998; Ogola *et al.,* 2002; Hinton *et al.,* 2003; Jonsson and Fold, 2011). Generally, in Africa, an estimated 9 million people are engaged in artisanal gold mining activities with another 54 million depending on the sector as an indirect livelihood source (Foster, 1996; Hilson, 2001; Valenzuela and Fytas, 2002; Jonsson and

Bryceson, 2009; Jonsson and Fold, 2011).

The extent and effect of gold mining activities on the earth's surface and especially in the developing countries can be assessed using a multidisciplinary approach (Luise and Cornelia, 2011). A spatial and field data collection analytical approach may be one of the most significant advances in understanding the characteristics and magnitude of gold mining pits in relation to sediment loading (Rajesh, 2004). The multidisciplinary approach may be supplemented by a combination of hydrodynamic, physio-chemical and biological analyses (Le *et al.,* 2006; Zuo *et al.,* 2012) to understand the effect of mining activities on the streamflow.

However, it is also important to note that, many hydrological studies have investigated the effect of gold mining activities on the environment and health, particularly in the form of heavy metal pollution (LaPerriere *et al.,* 1985; Malm, 1998; Grandjean *et al.,* 1999; Van-Straaten, 2000; Ogola *et al.,* 2002; Mol and Ouboter, 2004; Eisler, 2004) and sediment loading mainly attributed to rainfall-runoff erosion (MartĂn-Vide *et al.,* 2010). However, examining the effects of human-induced sediment loading due to gold stone washing in streams in the tropical catchments in relation to streamflow variations is an under researched area (Chen *et al.,* 2007). Therefore, the purpose of this study was to bridge this knowledge gap by assessing the extent and effect of gold mining activities (human-induced sediment loading) on the concentration of sediments and streamflow variations in the Okame River Micro-catchment.

5.2 Methods

5.2.1 Description of study area

The study was conducted in the Okame River micro-catchment, which is one of the major tributaries of the Malaba River catchment. The catchment was selected for sediment loading assessment because of widespread artisanal gold mining activities than in River Solo and Aturukuku catchments. The river joins the Malaba River, which later pours its waters into the Lake Kyoga. The Okame River originates from the hills located in western Kenya. The upstream part of the catchment is in Kenya (60 percent), while the downstream section is in Uganda. The size of the micro-catchment is 149.3 km^2. The micro-catchment tributaries include Omanyi, Nankuke, Namukombe and Nabewo Rivers, which discharge their waters into the Okame River (Figure 5.1). The catchment is dominated by an undulating plain type of topography with an altitude of approximately 1,128 metres above sea level.

The study area is shielded by the Pre-Cambrian rock types, which include granites, gneisses, quartzite and metamorphic rocks (Barasa *et al.,* 2011). The soils fall under the ferrallitic soil catena group, which is mainly composed of sandy-loams. The soil layers have little differentiation in their horizons, possessing a fine granular structure, often moulded into layers, with weakly coherent clods which are very friable and porous (Otieno and Buyinza, 2010). The catchment experiences an average annual rainfall of 1,514 mm/year. The rainfall pattern is bimodal, with the first rainy season (short rains) starting from March to May and a longer rainy season extending from August to November. The mean annual maximum temperature is 28.7 °C, while the mean annual minimum temperature is 16.2 °C. The vegetation observed in the catchment has undergone considerable changes mainly due to the expansion of cultivated land, gold mining and settlement. The main sources of livelihood are subsistence agriculture, gold mining, and petty businesses among others.

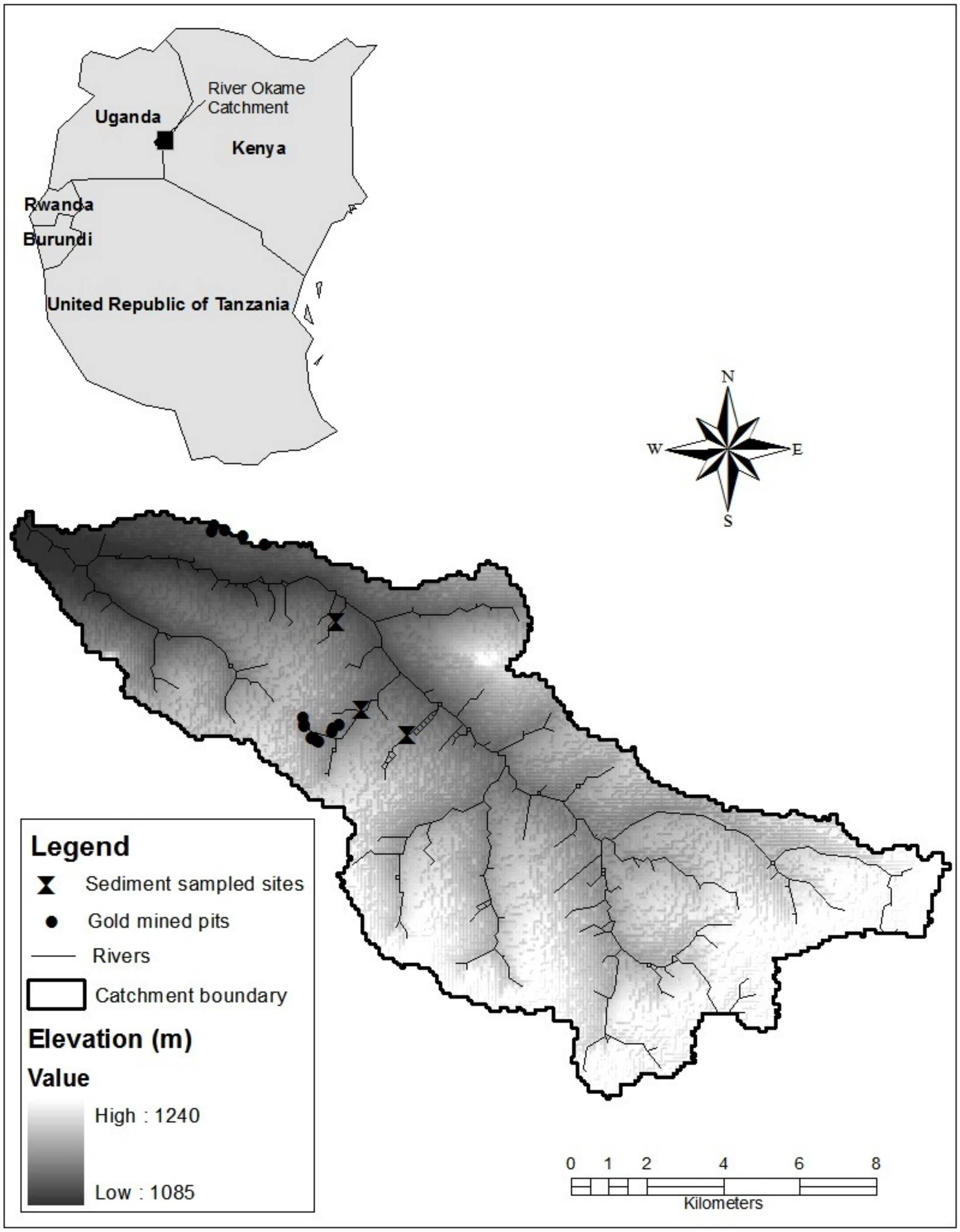

Figure 5.1: The Okame River Catchment and the sampled sites (tributaries)

5.2.2 Gold mining in the catchment

Gold was discovered in the catchment in 1932 and prospected in 1994, but it was until recently that actual mining has started with open cast mining (Roberts, 1986; Schlüter, 2006). The goldfield occurs in volcanic rocks of greenstone-type in the extreme southeast of Uganda, where the mineralization continues across the international boundary of Kenya to become the Kavirondo goldfield (Roberts, 1986; Kuehn *et al.,* 1990; Schlüter, 2006). However, gold mining activities are more rampant in the sub-counties of Busitema and Buteba in the Busia District of Uganda; covering an approximate area of about 134.6sq.km. The catchment has one of the largest gold mine deposits in the East and Central Africa. The extracted gold by the artisanal and small scale miners is processed following procedures described by Telmer and Veiga (2009).

5.2.3 Sediment and streamflow data collection

Streamflow, suspended and river bed deposit sediment data were collected from the selected stream cross sections on a monthly basis for a period of one year (2012) from the three selected gold washed streams (Omanyi, Nabewo and Nankuke Rivers). The streams were selected because they exhibited similar hydrodynamic properties. This sampling time-frame was adopted because sediment data collected and analysed with a low frequency has better prediction results (Horowitz, 2003). The streamflow, suspended and river bed deposit sediment data were collected at tributary level other than in the main Okame River, because of a high diversity of land surface conditions, human activities and high hydrological time lag of rainfall runoff (Lu *et al.,* 2003). Also, most sediment discharges in catchments come from small areas found within catchments (Xiaoqing and Yang, 2003). The sediment data were collected from sections of high flow prior to gold stone washing and after the washing process had taken place from the sampled streams.

An instantaneous sampler was used to collect sediment water samples at one level and in the middle of each sampled stream because of the low the stream hydrodynamic properties (stream depth, discharge, width) (John, 2011). The water samples were taken to the laboratory for sediment and bed load measurement. In the laboratory, sieves of 63μm were used to remove coarse suspended sediments from the water samples. Approximately, 25 - 100 ml of water from each sample was filtered onto a pre-ashed and pre-weighed GF/F 25 mm filter of pore size 0.45μm, which was then dried at 60 °C at constant weight before weighing. A flow-probe (model FP211) was used to measure stream discharge from the sampled streams.

The river bed deposit materials were sampled using a Van Veen grab sampler (Azamathulla *et al.*, 2009). The river bed deposit samples were also delivered to the laboratory for grain-size analysis. In the laboratory, the samples were oven dried at 105 °C for 24hours, weighed (300 g) and sieved on a sieve shaker for 30 minutes to get the grain-sizes. Gold ore washing was dependent on the largest particle size in the sample. The particle sizes were classified following the USDA Soil Survey Staff (1975) particle size classification scheme. The data were analysed using a linear mathematical relationship between the logarithmically transformed sediment concentration and discharge through regression analysis (Quilbé *et al.*, 2006; Gao, 2008). The relationship was later tested for its significance using a Student's *t*-test. A one-way analysis of variance was carried out to test the significance of the bed deposit particle sizes in relation to the sampled streams. The study also calculated the daily suspended sediment loads per day from the sampled streams using an established equation by the United States Army Corps of Engineers (1995). The equation is as follows

$$Qs = K.c.q \tag{1}$$

Where Qs = sediment discharge (kg/day), c = sediment concentration (mg/l), q = water discharge (m^3/s), and K = 86.4.

5.2.4 Quantifying the extent of gold mining in the catchment

The study utilized both very high and high resolution imagery to quantify the extent of the gold mining land use. The images were pre-processed and processed differently since the satellite data acquisition modes were different. For the very high resolution, the pre-processed level-1 TerraSAR-X (ScanSAR) image acquired on 21st May, 2008 was obtained from the German Aerospace Centre (DLR). An overview of the TerraSAR-X satellite, its data modes, and future developments are described by many scholars (Bamler *et al.*, 2006; Zhiyong *et al.*, 2009; Liu *et al.*, 2011; Ortiz *et al.*, 2012). The image was provided as a Single Look Slant Range Complex product

(Figure 5.2). The TerraSAR-X image was adaptively filtered using an Enhanced Lee (Ortiz *et al.,* 2012) procedure and processed using an object-oriented classification algorithm in ENVI 4.7 software. The software showed low deviations in the area and shape of the pits (Neubert and Herold, 2008).

For the high resolution image, an ortho-rectified and cloud-free Landsat TM/ETM+ imagery of 30m grid-cell reflective size was acquired on 2013-04-19, (Path 170 and row 60; zone 36N). The Landsat imagery was filtered using the majority (3 x 3) filtering method and stretched using a linear approach prior to its classification (McDonnell, 1981; Cleve *et al.,* 2008). A hybrid approach of unsupervised and per-pixel based segmentation was utilized in the classification of the gold pits. The approach was ideal because of the heterogeneous nature of the gold pits and their spectral reflectance (Lucas *et al.,* 2007).

The classified images were verified with the help of field information for a more accurate classification. However, information on the history, characteristics and distribution of gold pits was obtained from the local area key informants. The physical attributes of these pits were also obtained by measuring their geometry (depth, size, and water level) using a measuring tape. The change rate of the gold mined pits was computed following Peng *et al.* (2008) procedures.

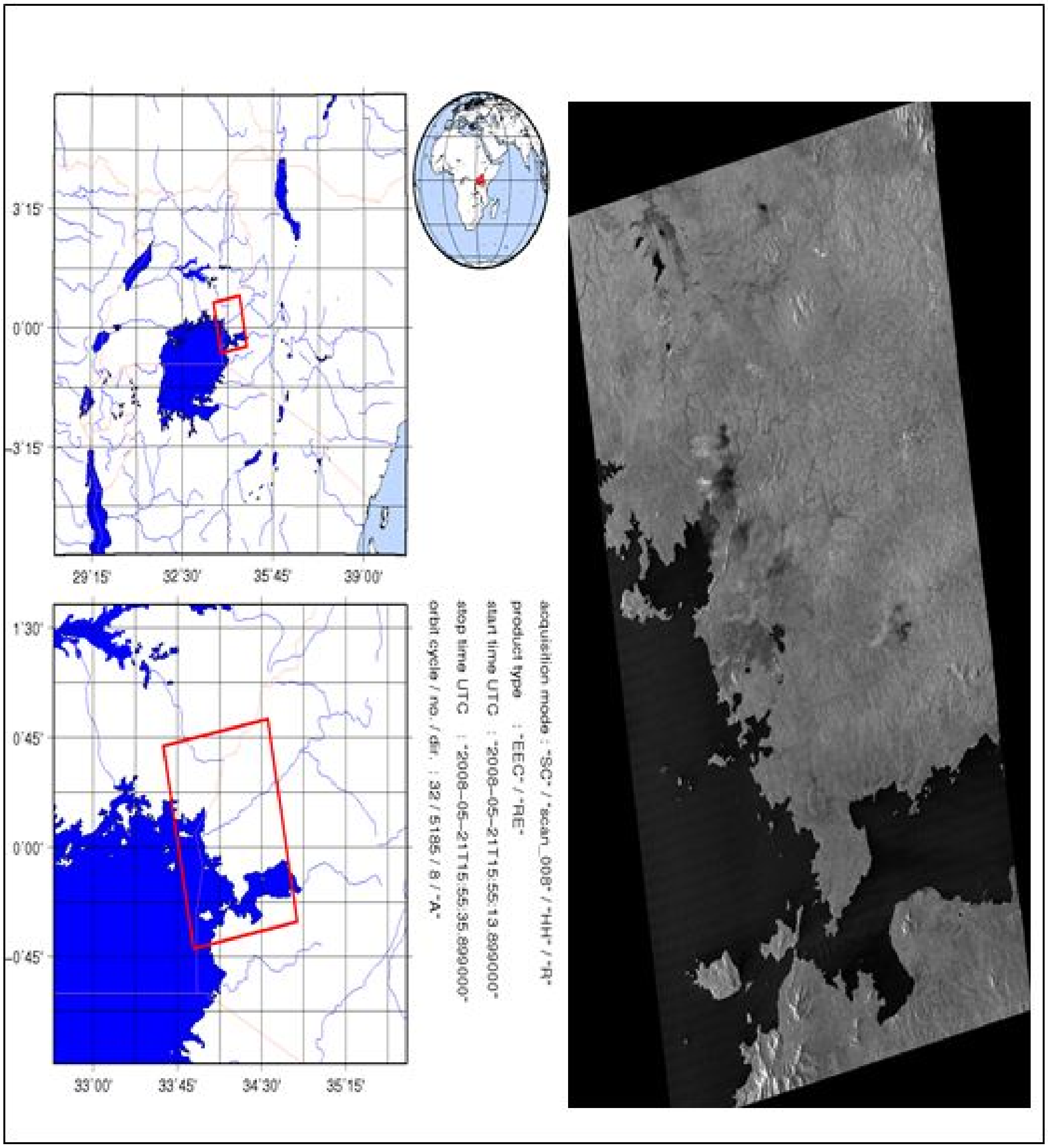

Figure 5.2: TeraSAR-X(X-HH) acquisition scene by the satellite)

5.3 Results

5.3.1 Characterization and classification of gold mined pits

Gold mining in the catchment is widespread. This is dominated by artisanal gold miners and a few are operating on a commercial basis. The commonest types of gold pits were of the rectangular type, followed by the circular ones. The circular types were reached after a continuous deformation of the laid-out rectangular pits in the early stages of extracting gold ore. The average depth of the rectangular pits was 16.3 m, while 5.1 m for the circular pits was. On average, each pit was accessed and mined by approximately 22 people annually (Table 5.1).

Characteristics	**Variable**	**Parameters**
Morphology	Altitude	1137m
	No. of pits sampled	33
Pit geometry	No. of Rectangular	24
	No. of Circular	9
	Av. Rectangular area	40m
	Av. Circular area	193.4m
	Mean pit depth (circular)	5.1m
	Mean pit depth (rectangular)	16.3m
Landscape slope type		Gently Sloping
Land use	Dominant land use and cover	Subsistence farming, gold mining, wetland
Labour	Annual average number of miners per pit	22
Soil	Soil composition type	Sandy loam soils
	Parent materials	Volcanic and metamorphic rocks
Accessibility	Gold pit accessibility	Leasehold/ hiring
	Land tenure	Customary system
	Mineral type	Gold
	Frequency of mining	Permanent
	Area accessibility	Moderately accessible

Table 5.1: Characteristics of the sampled gold mined pits

5.3.2 Extent of gold mining land use

The classification results showed that there is a large increase in the extent of the gold mining, which covered a relatively large portion of land. In 2008, the mined area covered 4.5sq.km and increased to 19.9sq.km in 2013. The annual rate of change of gold mining land in the studied period was 15.5 percent. Most of the mining activities occurred in the upland areas than in low lying areas (wetlands and river bottoms) (Figure 5.3). The extracted gold ore were ground and later washed in the nearby streams.

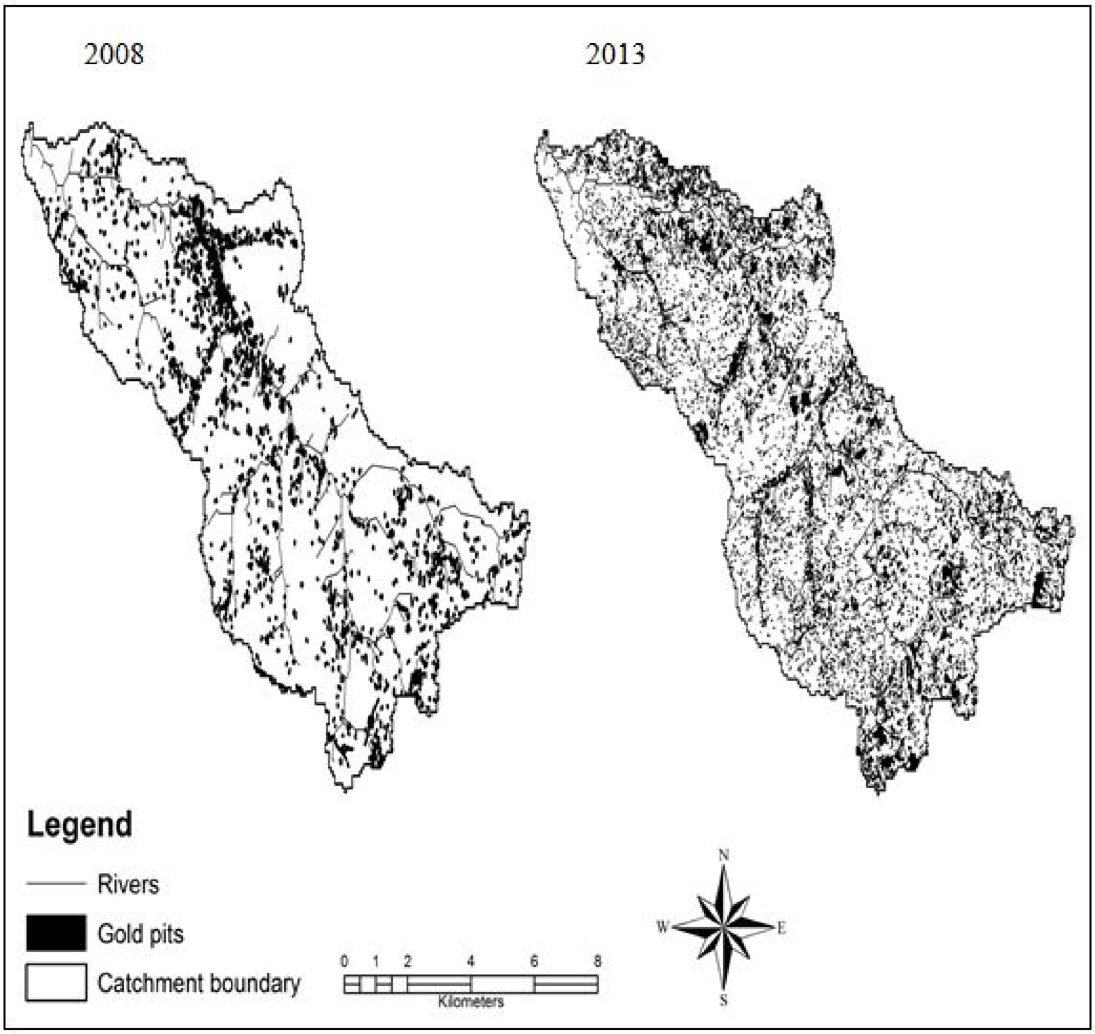

Figure 5.3: Map shows the extent of gold mining land use in the catchment between 2008 and 2013

5.3.3 Sediment loading and concentration

5.3.3.1 Concentration of suspended sediments

The results showed that human-induced sediment loading due to the washing of gold ore in the rivers had a high impact on the concentration of suspended sediments (CSS) than the natural process (surface and bank erosion) from the sampled streams. Prior to human-induced sediment loading, the highest concentration of suspended sediments was 160 mgl $^{-1}$, while after gold washing the concentration increased upto 864 mgl^{-1}. Under the natural process, the highest CSS was recorded in Omanyi River (808 mgl^{-1}), followed by Nabewo (244 mgl^{-1}) and Nankuke (160 mgl^{-1}) Rivers. After the gold washing, the highest CSS was still recorded in Omanyi (878 mgl^{-1}) river followed by Nankuke (864 mgl^{-1}) and Nabewo (465 mgl^{-1}) rivers (Figure 5.4).

These variations in the CSS also varied from one month to another. For instance, before the human-induced loading, the CSS was nearly related to the rainfall events experienced in the catchment especially in the months of March-April and October-November. However, the CSS was relatively high in the dry months across the sampled gold washed streams (Figure 5.4).

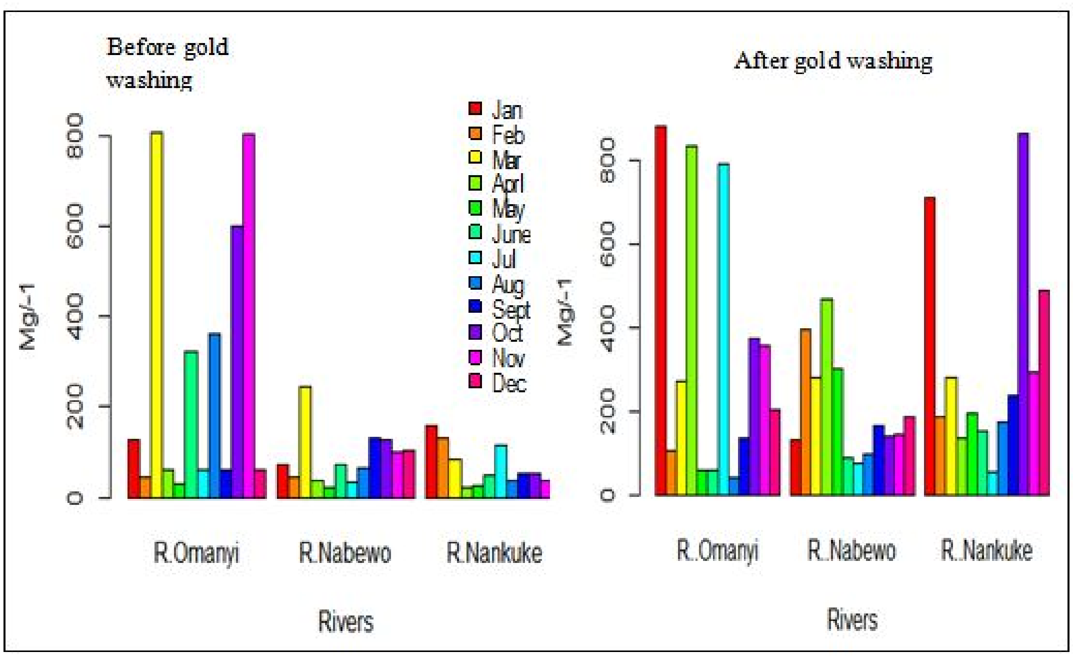

Figure 5.4: Suspended sediment concentration before and after gold sieving (washing) in the sampled rivers

Before gold washing, the highest contributor of suspended sediments to Okame River was Omanyi River (47.7 kg/annum), followed by Nankuke River (29.9 kg/annum), and then Nabewo River (26.5 kg/annum). The main contributor of human-induced sediments to the Malaba River was Nankuke (130.6 kg/annum) River followed by Omanyi (70.6 kg/annum), and lastly Nabewo (66.8 kg/annum) River. The study results reveal how mining contributes to the increase of suspended sediments loaded from the sampled streams into the Okame River. In particular, the sampled streams contribute approximately 372 kg/annum of suspended sediments delivered to the Okame River micro catchment (Table 5.2).

	Before gold sieving (kg/day) *10^3			After gold sieving (kg/day)*10^3		
Months	**Omanyi R.**	**Nankuke R.**	**Nabewo R.**	**Omanyi R.**	**Nankuke R.**	**Nabewo R**
Jan	1.09	2.76	1.24	7.59	24.47	3.32
Feb	0.76	6.79	1.22	2.70	8.08	13.62
Mar	6.98	3.63	8.43	4.70	9.61	7.21
Apr	1.07	0.86	1.24	21.51	4.67	12.05
May	0.25	0.62	1.71	0.49	8.29	7.78
Jun	2.80	2.49	1.84	1.00	6.52	1.52
Jul	0.52	3.02	0.56	20.42	1.85	3.24
Aug	6.29	1.56	1.12	0.69	5.98	2.44
Sep	1.07	1.40	2.28	3.53	10.20	2.83
Oct	5.20	1.35	3.27	3.23	22.39	4.80
Nov	0.87	1.28	1.75	3.08	7.52	4.91
Dec	1.07	3.63	1.78	1.75	21.04	3.18
Total	47.97	29.39	26.45	70.69	130.61	66.89

Table 5.2: Concentration of suspended sediments transported by the streams

5.3.3.2 Suspended sediment concentration and stream discharge

Streamflow from the sampled streams did not vary despite having different amounts of sediment concentrations. This was reflected in the weak coefficient of determination obtained between the CSS and streamflow before (Omanyi R. (r^2=0.003), Nankuke R. (r^2 =0.01), Nabewo R. (r^2=0.22) and after (Omanyi R. (r^2 =0.001), Nankuke R. (r^2=0.07), Nabewo R. (r^2=0.009) gold washing (Figure 6.5). However, this correlation was statistically significant ($P<0.05$, Student *t*-test) for all the sampled streams.

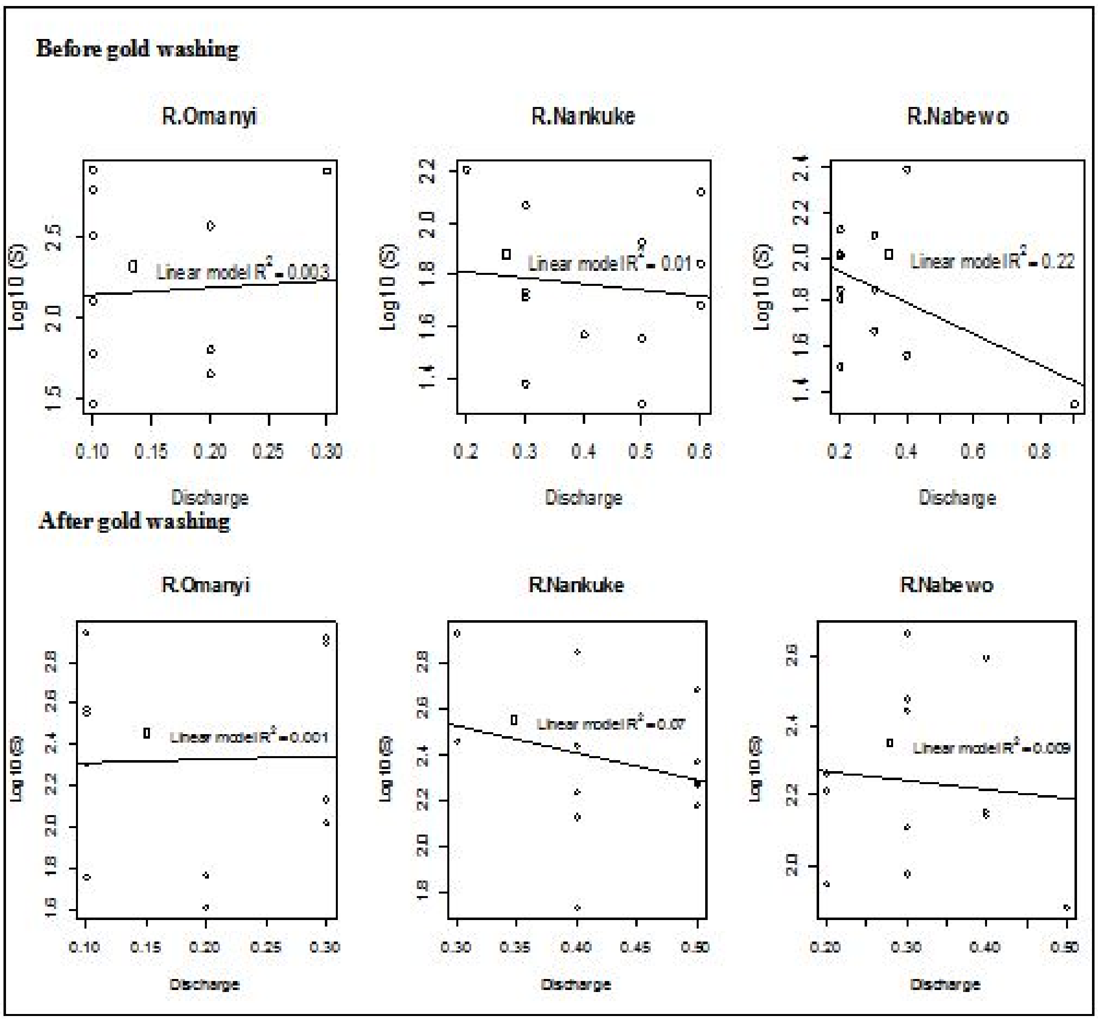

Figure 5.5: Sediment concentrations (S) in relation to discharge, after logarithmic transformation of S (n=12), S: Sediment concentration (mg l^{-1}); Discharge (m^3s^{-1});) in the three sampled streams

5.3.4 River bed deposit

5.3.4.1 5.3.4.1 River bed deposit cumulative curve

Figure 5.6 shows the sampled river bed deposit sediment frequency distributions representing the three sampled streams. For the studied period, thirty three (33) percent of the recorded river bed deposit particle size was less than 21.2 mm particle size. The largest river bed deposits weighed 6mm (88%) from the sampled streams (tributaries).

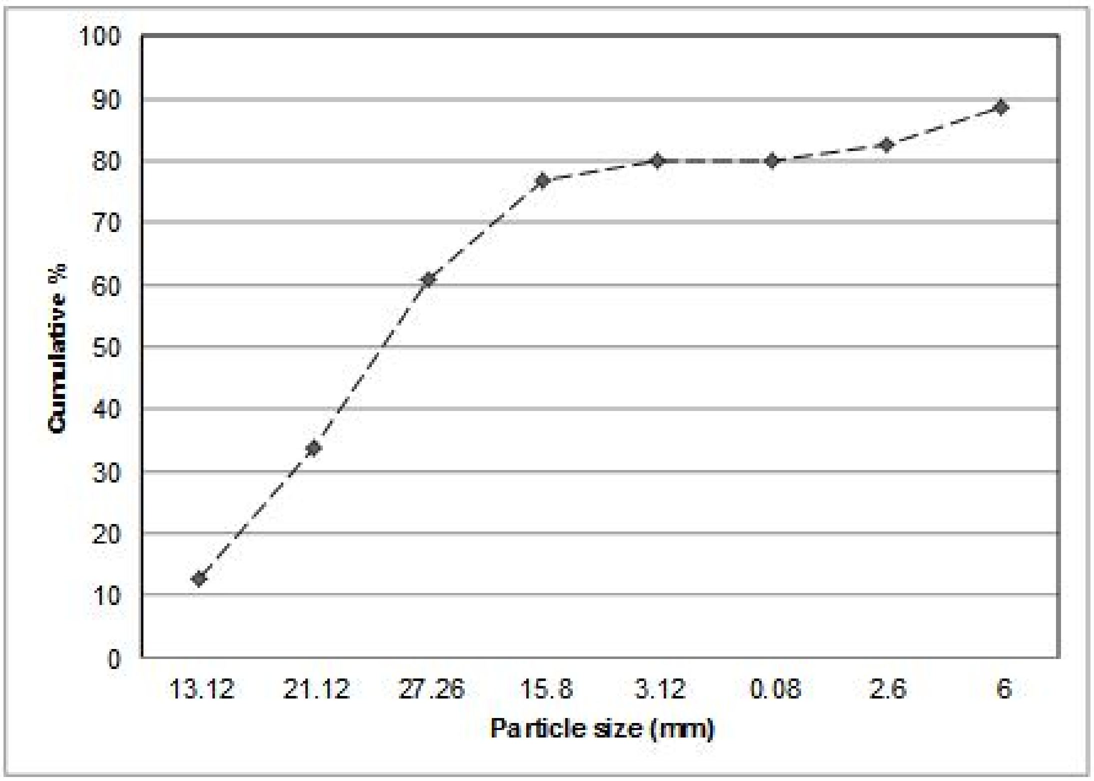

Figure 5.6: River bed deposit cumulative arithmetic curve

5.3.4.2 River bed deposit and streamflow

The river bed deposit particle size distribution is an important reference for the assessment of the effect gold mining activities on the streamflow. In this regard, the study results showed that, the most predominant river bed deposits that dominated the river channel bed (before and after gold washing) from the sampled streams were fine sand (0.25 mm) and fine gravel (4 mm).

The least types of river bed deposits grain-sizes were the very fine sand and clay. The high presence of sand-related particle-size types is reflected in the strong relationship (R^2=0.88 and 0.85) between the coarse and medium sand respectively. This meant that the coarse and medium sand, and also silt had the most significant impacts on the distribution and determination of the sizes of the other river bed deposits found in the sampled river bottoms ($P<0.05$). The river bed deposits also played an important role in the increase of suspended sediment concentration and fluctuation of streamflow from the sampled streams.

Statistically, there was no significant difference between the sampled rivers and the gold washed sites (before and after gold washing). Though, there was a significant difference between the very coarse and coarse sand, and the sieved/washed and non-sieved/washed sites ($P<0.05$). However, coarse sand was the only statistically significant particle size between the sampled streams and in the sampled period. These results indicated that the statistical significance in the river bed deposits particle sizes determined the river functions and streamflow fluctuations.

P=Values Sieve				**particle sizes (mm)**				
Sieve size	**4**	**2**	**1**	**0.5**	**0.25**	**0.125**	**0.063**	**< 0.063**
Grain type	**FG**	**VCS**	**CS**	**MS**	**FS**	**VFS**	**Silt**	**C**
R^2	0.65	0.83	0.88	0.85	0.76	0.72	0.83	0.79
Overall ANOVA	0.72	0.06	0.01*	0.03*	0.24	0.41	0.05*	0.16
Sampled rivers	0.95	0.02*	0.09	0.13	0.43	0.30	0.69	0.14
Months	0.08	0.48	0.01*	0.01*	0.04*	0.03*	0.02*	0.01*
Treatment	0.63	0.81	0.04*	0.77	0.92	0.68	0.82	0.77
River and Months	0.93	0.13	0.03*	0.48	0.38	0.69	0.90	0.64
River and Treatment	0.96	0.85	0.28	0.14	0.29	0.45	0.09	0.75
Months and Treatment	0.90	0.01*	0.03*	0.93	0.66	0.99	0.01*	0.84

Table 5.3: A comparison of P values ($P< 0.05$) from the distribution of river bed deposit particle sizes

Significant* ($P<0.05$). **Soil type: FG= Fine gravel; VCS= Very coarse sand; CS=Coarse sand; MS= Medium sand; FS= Fine sand; VFS= Very fine sand; S=Silt; C=Clay. **Treatment:** sampled sites:

Before and after Gold sieving.

5.3.4.3 Gold mining activities

Figure 5.7 shows the nature of gold pits, pounded gold ore ready to be washed in the streams and human induced sediment loading and diversion of the river channels. Gold is mined from both the upland and river bottoms. The mined ore are manually pounded and sieved with mesh to separate the particles. The fine ore are later washed in the rivers. The washing process results in the diversion of river courses and draining of the wetlands and river to mine river bottoms.

Figure 5.7: Gold mined pit (a), pounded gold stones/grain (b), sieving/washing of gold (c) and river bottom gold mining (d)

5.4 Discussion

The study revealed that the continued extraction and washing of gold ore in the tributaries of the Okame River throughout the year explains why human-induced sediment loading had a much higher impact on the concentration of suspended sediments (CSS) and distribution of river bed deposit particle sizes. This has caused significant variations in the streamflow than surface rainfall-runoff from the sampled streams. This finding is also in agreement with the observations made by Milliman (2001) and Walling (2006) that the drivers of increased sediment loads include land clearance for agriculture and other facets of land surface disturbance, including logging activity and mining. Houben *et al.,* (2006) also noted that the human factor is the major driving force of sediment production and re-distribution in streams. In addition, Syvitski *et al.,* (2005) also reported that humans have simultaneously increased the sediment transport by global rivers through soil erosion (by 2.3?0.6 billion metric tons per year), yet reduced the flux of sediment reaching the world's coasts (by 1.4 ?0.3 billion metric tons per year) because of retention within reservoirs.

On average about 35 kgs of particle grains are washed into the streams on a daily basis. This study notes that the sampled streams (Omanyi, R. Nankuke R., Nabewo R.) contributed approximately 372 kg/annum of suspended sediments in the Okame River; which is one of the major tributaries of the Malaba River. This is ought to cause profound effects on the fluctuation of the catchment overall streamflow. This finding relates to Dearing and Jones (2003) who argued that the human induced loading of sediments in rivers increases typically five to tenfold following a major human impact that causes drastic changes in the fluctuation of the streamflow.

The study also reveals that the less than 50 percent of the variance of CSS could not be explained by the streamflow. This low variation was attributed to the intensive loading of human induced sediments in the face of low stream power, changing climate and stream morphology. Syvitski and Milliman (2007) also found out that climatic factors (precipitation and temperature) account for an additional 14 percent of the variability in global patterns in sediment load; while the anthropogenic factors account for an additional 16 percent of the between river loads. This clearly demonstrates how the human impact contributes more to sediment load than rainfall-runoff.

The coarse and medium sand, and also silt had the most significant contribution on the distribution of particle sizes that were found on the sampled river channel bottoms. This was because of increased sediment supply (Jayne and Mossa, 1999). However, the washing of river bed deposit materials in search for gold caused incision of the channel bed (Kondolf, 1994), channel enlargement, shrinking and metamorphosis (Gregory, 2006). However, the river bed deposit transport rate was governed by higher slope-sensitive capacity limits (Moss and Walker, 1978).

Nevertheless, the rates of sediment deposition were higher in the dry season than in the rainy season (Refer to Table 5.4). This was because the artisanal miners engaged more in crop farming since the active mining pits were filled with water. This is in agreement with the findings of Hinton *et al.* (2011) who supplemented that most of artisanal and small scale mining activities in Uganda are informal and unlicensed and in many cases there are undertaken seasonally to supplement agricultural livelihoods. The high amount of sediments deposited in the streams results into, stream course diversion, reduced water levels, colonization of stream banks by vegetation, which slowed down streamflow. Gradziñski *et al.,* (2003) also found out that the riparian vegetation stabilizes channel banks and slows down the water flow.

The magnitude of gold mining land use increased in the catchment as noted earlier; the mined area expanded from 4.5 km^2 in 2008 to 19.9 km^2 in 2013. This rampant growth in the number of mined pits was largely attributed to livelihood diversification, customary land tenure system, local and international demand for gold, weak enforcement of environmental and mining policies and bureaucracy in the acquisition of mining permits and licenses. This is similar to the findings of Siegel and Veiga (2009); Hilson (2009); Bryceson and Jonsson (2010); Banchirigah and Hilson (2010); and Maconachie (2011) who noted that livelihood diversification in the rural Sub-Saharan Africa is focusing primarily on the growing economic importance of artisanal and small-scale mining in the region. In addition, Foster (1996), and Jonsson and Bryceson (2009) also found out that the spread of artisanal gold mining activities is spurred by the availability of gold as a highly valued commodity in the region and worldwide. However, this study is also in conformity with the view that almost one third of all active mines in the world are located in water stressed catchments (Millennium Ecosystem Assessment, 2005).

5.5 Conclusion

This study reveals that human-induced sediment loading had a higher impact on the concentration of suspended sediments and fluctuation of discharge than sediments from rainfall/stream bank runoff from the sampled streams. This has caused significant variations in the streamflow than surface rainfall-runoff from the sampled streams. This impact was normally higher during the dry months than when the catchment is wet. From the studied streams, the main contributors of human-induced sediments were Nankuke, Omanyi, and Nabewo Rivers. This has resulted into stream course diversion, reduced water levels, colonization of stream banks by vegetation, which slowed down streamflow. This study has bridged the knowledge and research gap because most sediment loading studies in East Africa were normally carried out at the lake level and not at the tributary level (Kishe and Machiwa; 2003); where their point sources are not clearly defined (Kimwaga *et al.,* 2012).

This chapter (five) focused on assessing the extent and effect of gold mining on sediment loading and their implications for the variation of streamflow of the Okame River Micro-catchment. The subsequent chapter examines the effect of land use and cover change on the river channel morphology and their implications for the variation of streamflow in the Solo River Sub-catchment. This chapter addresses the variability of land use on river bank stability and streamflow due to sediment loading from surface rainfall-runoff from different land use and cover options. This chapter complemented the results obtained from the previous chapters that fell short on the behavior of the river channel in response to changes in land use and cover options.

Chapter 6

Assessing the effect of land use and cover change on the river channel morphology and their implications for the variation in streamflow of the Solo River Sub-catchment, Eastern Uganda

Abstract

The effect of land use and cover change on the river channel morphology in the tropical regions are largely dependent on the significant land use types, amount of precipitation received and river stages. This effect was studied through the collection of samples (soil, water and river bed deposit) to assess the concentration of sediments and river bank/channel stability. In addition, the river was surveyed at the laid out cross-sections to determine the dynamics of river channel aggregation and degradation. The assessment showed that the wetland (537.1mgl^{-1}) cover type had the highest concentration of suspended sediments, followed by bushlands (186.3mgl^{-1}), tree-plantation (156.9mgl^{-1}), tropical forest (70.6mgl^{-1}) and agricultural (89.1mgl^{-1}) landuse. Fine sand (0.25mm), silty sand (1mm) and silty clay (0.125mm) river bed deposit particle sizes dominated the river channel bottom. The tree plantation (cohesion=12, angle of internal friction=27) and bushland (cohesion=14, angle of internal friction =22) land cover types had the most stable river banks compared to those under bushlands and agricultural land use (crop growing) and cover types. The highest rates of both channel aggradation and degradation were experienced from the agricultural landuse than in the tree plantation land cover type. This has resulted into the diversion of the river course through the narrowing and widening of the river channel along the changing landuse and cover types in the sub-catchment.

Keywords: River channel morphology, streamflow, land use and cover, sediments

6.1 Introduction

River channel morphology adjusts to changes in streamflow, land use and cover (Madej and Ozaki, 1996), boundary materials and valley topography (Thorne *et al.*, 1996). River channels are also sensitive to the impacts of climate change, (VanLooy and Charles, 2005) especially during the occurrence of floods (Paquier and Saeed, 2002). The resilience of river banks to this change depends to a great extent on the presence of plant roots (Rosgen, 1994; Stefano *et al.*, 2011). The land use and cover changes may be accelerated by the human modification of land cover. This causes stronger geomorphic responses such as increased sediment supplies, transport and deposition regimes (Liebault *et al.*, 2005; Qazi and Ashok, 2011).

The drivers of human-induced changes are attributed to the demand for cultivatable land, commercial timber harvesting, and urbanization (Taillefumier and Pié gay, 2003). Elsewhere, in about 150 major watersheds in North America, agricultural land use varied from near zero in some northern river systems to 66 percent in the Upper Mississippi Basin for the last 20 year period (Allan, 2004). While in East Africa, about 13 million hectares of original forest cover have been lost over the same 20 year period; and the remaining forests are fragmented and under threat (FAO, 2010). The major factors affecting alluvial stream channel forms are stream discharge, sediment load, longitudinal slope, river bank and bed resistance to flow, vegetation and geology (Darby and Thorne, 2000). These factors are governed by the mixing of river water (Yang *et al.*, 2001) and the hillsides; though the pattern of sediment load reacts to what is happening on the slopes and the channel (Keller *et al.*, 1997).

Although the general causes and effects of sediment supply and channel changes are well-defined; the ranges of possible channel responses are unclear (Clark and Wilcock, 2000) because they may be initiated by an increase or decrease in either water or sediment load (Qiang *et al.*, 2008). Sediments injected by tributaries from upstream land degradation and bank erosion can be redistributed downstream resulting into channel narrowing (Shi *et al.*, 1999). The variability in sediment delivery, hydraulic discharge and channel slope may give rise to spatial and temporal variations in the channel morphology and its response (Montgomery and Buffington, 1998). The potential channel adjustments to land use intensification and bank erosion may include changes in stream width, depth, velocity, slope, roughness and sediment size (Gregory, 2006).

Examining river channel adjustment is important in evaluating future flood risk and morphological changes (Gilvear, 2004; Cluett, 2005). River channel assessment is also necessary for the capital works and operational maintenance to avoid destroying further infrastructure (Thorne *et al.,* 1996), which might have been damaged or environmentally degraded (Downs and Thorne, 1996). The effect of land use and cover changes on river channel adjustments (such as channel widening and downstream aggradation) have a channel change ratio of about 0.05-15.0 meters at the surveyed cross section (Gregory, 2006). However, most studies have mostly concentrated on sediment transport in rivers to influence channel morphology (Ashmore, 1991). In addition, the influence of land use and cover change on the river channel morphology is not well documented for small catchments in the tropical region (Unde and Dhakal, 2009). This study also investigated the causes and effects of river bank instabilities on the channel morphology, streamflow and sediment concentration (Formann *et al.,* 2007). The Solo River sub-catchment is not exception from river bank instabilities because it is experiencing more frequent flood events that are severe. Therefore, the aim of this study was to bridge this knowledge gap by assessing the effect of land use and cover change on the river channel morphology and their implications for the variation in the streamflow of the Solo River Sub-catchment.

6.2 Materials and Methods

6.2.1 Description of Solo River Sub-catchment

This study was conducted in Solo River sub-catchment, which is also one of the tributaries of the Malaba River. The river originates from the two main valleys found in Busia municipality in Uganda. The size of the catchment is 71.8sq.km (Figure 6.1). The catchment was selected for this study because it experienced the highest rates of runoff depth during the rainfall events attributed to the impervious surface from Busia town centre, and overland flow from the cultivated lands. The catchment has an annual average temperature of 27.9 °C. The highest temperatures are experienced in the months of January to March with 29.3 °C respectively. The annual minimum temperature is 15.9 °C, which is experienced in the months of March to May and October to December. The highest amount of precipitation is received in the months starting from March to May (280 mm/month, 240 mm/month) and August to November (183 mm/month, 170 mm/month).

Sandy-loam and clay are the major soil types that underlie the sub-catchment. The sandy-loams are found in upland areas, while the clays are in the valleys (i.e. wetlands). These soil types have a little difference in their defining soil-layer horizons. The soil types fall under a soil catena group of, Petric plinthosols, and Gleysols (NEMA, 1997). The most predominant land use and cover types are subsistence agriculture (crop growing) and tropical forest (fully stocked) followed by the degraded tropical forest areas, bushlands and woodlands.

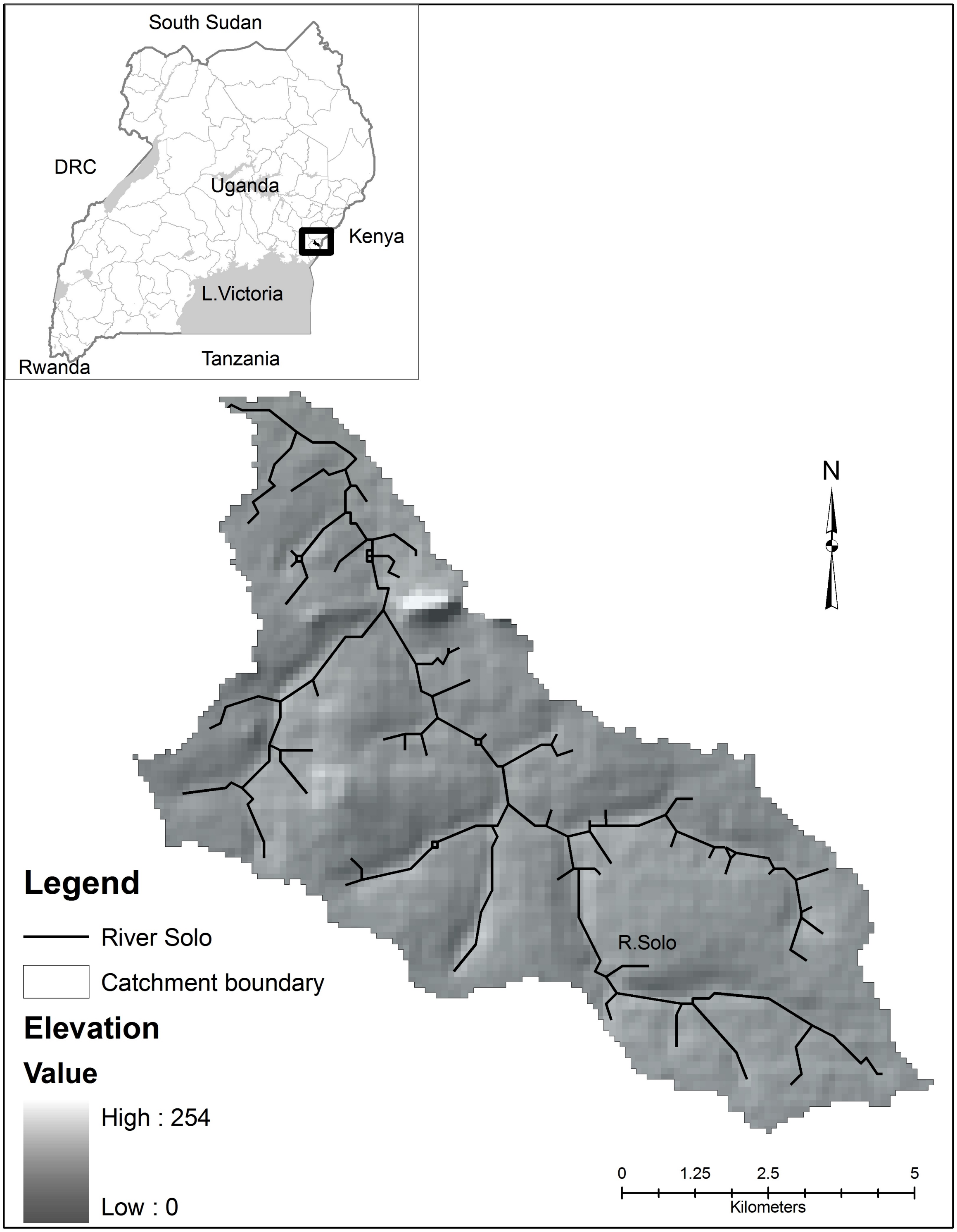

Figure 6.1: River Solo Sub–catchment

6.2.2 Data collection and analysis techniques

6.2.2.1 Channel planform change

The use of remote sensing and geographical information system's based data in the monitoring of river channel morphological permits the interpretation of catchment-wide channel trends and their associated instabilities (Thorne *et al.,* 1996). In this respect, two sets of ortho-rectified and cloud free Landsat TM/ETM+ (30m, band 5 and 7) images of 1986 and 2013 were downloaded (http://glovis.usgs.gov/) and pre-processed using the majority filtering method (Mouchot *et al.,* 1991) prior to information extraction. The planform change was extracted and assessed for the river channel connectivity from the selected image bands. The selected bands had a moderate distinctive reflectance signature that allowed the channels to be mapped (Leal, 2002). The planform change was quantified by cross-tabulating the attributes of the channel classes (erosion/deposition/no change channel) within the specified spatial units or polygons defining the channel reaches (Maidment *et al.,* 1994) for each particular cross-section. The channel coverage per year was determined following Maidment *et al*. (1994) procedures. However, this study did not map the river channel planform change under the area covered by the tropical high forest (Busitema - Forest Reserve) because of accessibility.

6.2.2.2 Suspended and river bed deposit sediments

Streamflow data, water, and river bed deposit samples were collected on a monthly basis for a period of one year (2012) from the selected land use and cover types (agriculture, bushlands, tree plantation, and wetland) along the river. The sampling protocol was set and strictly followed for quality assurance. An instantaneous sampler was used to collect the water samples at one level due to the river channel dynamics. The samples were then delivered to the laboratory for analysis. In the laboratory, sieves of 63μm were used to remove the coarse suspended sediments from the water samples. Then, 25 - 100 ml of water from each sample was filtered onto a pre-ashed and pre-weighed GF/F 25 mm filter of pore size 0.45μm; and then dried at a constant weight at 60 °C before weighing. Streamflow was measured using a handheld flow-probe (model FP211).

The river bed deposit materials were sampled using a Van Veen grab sampler (Azamathulla *et al.*, 2009), and then delivered to the laboratory for grain-size analysis. The samples were oven dried at 105 °C for 24hours, all weighed at 300g and sieved on a sieve shaker for 30 minutes to get to the grain-sizes. Washing was dependent on the largest particle size in the sample. The river bed deposit particle sizes were classified following Xiaoqing and Yang (2003) index of soil stability for materials comprising of river banks and channel beds (∞_{bank} and ∞_{bed}). The principal factor analysis was carried out to determine the most predominant river bed deposit grain sizes from the sampled land use and cover types. The suspended sediment data were analysed following a one-way analysis of variance procedure to test the significance of land use on the channel morphology and river hydrodynamic parameters (discharge, suspended sediments, stream width, and depth).

6.2.2.3 River bank stability

A series of soil samples were collected along the river bank in the different soil profiles (horizons) from the sampled land use and cover types to determine the stability of the bank to channel aggradation or degradation in the sub-catchment. The undisturbed soil samples were subjected to a direct shear stress box test in the laboratory in accordance with the British Standard (BS-1377: pat7: 1990) procedures. This method permitted a direct shear test to be made by relating the shear stress at failure to the applied normal stress. Shear strength parameters (cohesion and friction angle) were of primary concern in the examination of channel widening, narrowing and bank stability (Thorne *et al.*, 1996).

The soil profile bulk density was determined using a core method (Black and Hartge, 1986), because bulk density is an important parameter to describe the soil function. The stability of the river bank was also examined in terms of root availability and abundance to bind the soil particles together. The abundance of roots in the soil profiles was assessed following FAO (2006) procedures.

6.2.2.4 Cross sectional geometry

The river channel was examined using a cross-sectional analytical approach to determine its narrowing or widening. The study laid out multiple cross-sections (10) along the major land use and cover types to identify appropriate sites for morphological monitoring. Two cross sections were fixed after the river bends (areas of reach) and topographically surveyed for two years (2011-2012). The surveyed cross sections were fixed in the agricultural and tree plantation land use and cover types. The river cross-sections were surveyed with the use of a Garmin Global Positioning System (GPS), an automatic level, stadia rod and distance meters. This approach made it possible to approximate the conditions of stream bed deposit particle moving at the various levels of streamflow (Hardy *et al.,* 2005). The surveyed land use and cover types were purposively selected because they presented a series of stable and unstable natural bends and banks compared to the other land use and cover types. In addition, this study adopted a catchment-wide examination of the dynamics influencing the river channel morphology. These were examined through a conduct of 10 key informant interviews, including the local residents, and local government officials who were knowledgeable about the dynamics in the catchment. This was important because understanding the morphological channel adjustments must be considered in a broader catchment scale context (Raven *et al.,* 2010).

6.3 Results

6.3.1 Channel planform change

The river channel planform occupancy results showed that the catchment has experienced drastic changes in land use and cover, and channel size. In 1986 the channel planform was 3.7sq.km; while in 2013, it increased to 4.2sq.km. The current occupancy is very distinctive than in the 1980s. This was reflected in the decrease in size and shift of the channel in the studied period. The study also shows that the river channel reaches had an occupancy equivalent to 1km per section of the river. The occupancy of the river channel planform increased by 0.5sq.km in the studied period (Figure 6.2). The study noted that there is a decreasing (narrowing) trend in the occupancy of the channel planform in the catchment (Figure 6.3).

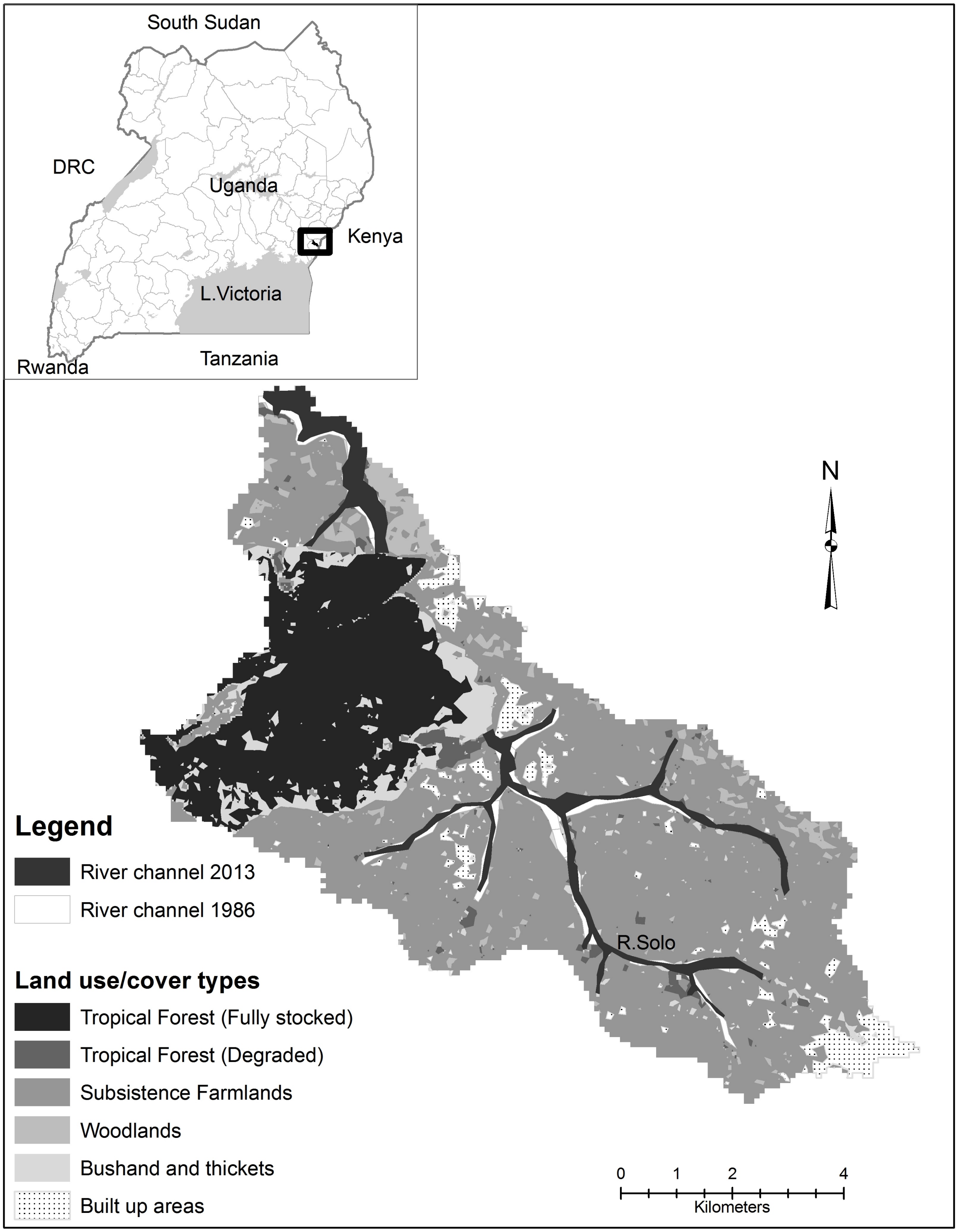

Figure 6.2: The channel planform of River Solo

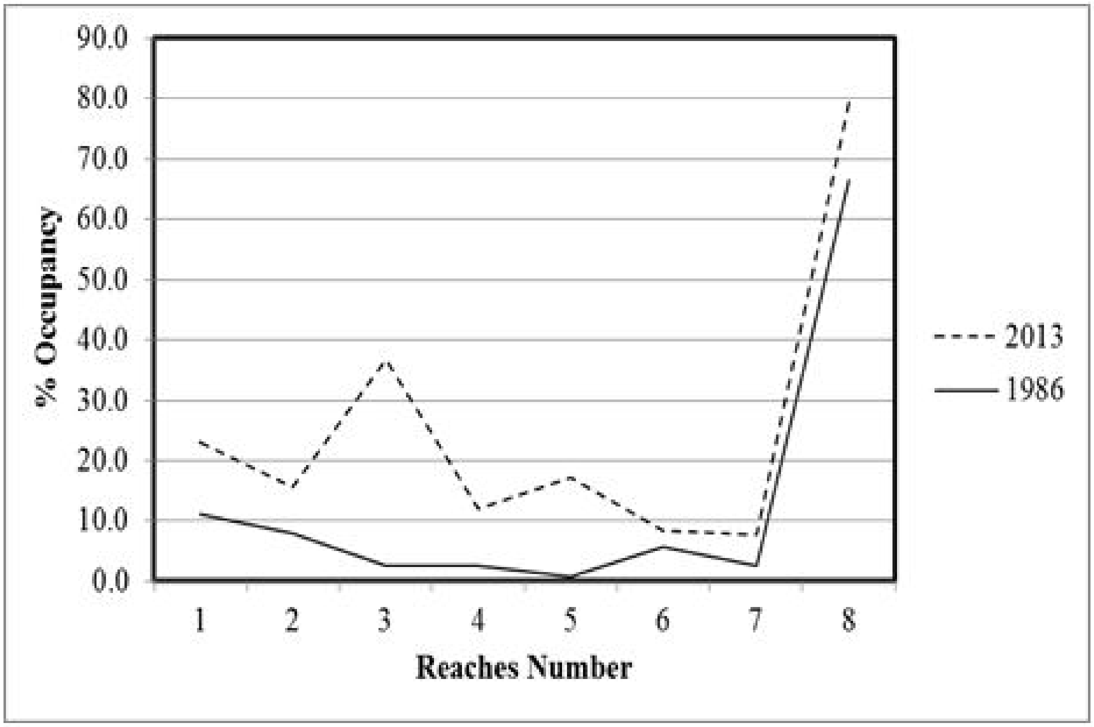

Figure 6.3: The occupancy of the river channel planform

6.3.2 Sediment and river bed deposit concentration

6.3.2.1 Suspended sediments concentration

The descriptive statistics for the measured concentration of suspended sediments are given below in Table 6.1. The highest distribution of concentrated suspended sediments was recorded from the wetland cover type with the mean value of 537.1 mgl^{-1}followed by bushlands (186.3 mgl^{-1}), tree plantation (156.9 mgl^{-1}), tropical high forest (70.6 mgl^{-1}) and lastly from agricultural (89.1 mgl $^{-1}$) land use. The concentration of suspended sediments with discharge is illustrated in Figure 6.4. This study reports that the higher the discharge rates, the higher the concentration of suspended sediments from the sampled land use and cover types.

Statistic	Agriculture	Tree plantation	Bushlands	Forest	Wetland
Units		mgl^{-1}			
Minimum	11.0	39.0	32.5	9.0	40.0
Maximum	160.0	708.0	786.0	184.0	3140.0
1^2 Quartile	38.1	53.8	46.0	39.9	111.3
Median	90.5	77.0	74.5	64.0	279.5
3^{rd} Quartile	128.8	122.0	166.0	77.8	584.0
Sum	1069.5	1883.0	2235.5	847.5	6445.5
Mean	89.1	156.9	186.3	70.6	537.1
Variance (n)	2403.0	36577.1	54251.7	2455.6	673759
Standard deviation (n)	49.0	191.3	232.9	49.6	820.8
Variation coefficient	0.6	1.2	1.3	0.7	1.5
Skewness (Pearson)	−0.2	2.0	1.7	1.0	2.6
Kurtosis (Pearson)	−1.3	3.0	1.4	0.2	5.5

Table 6.1: The descriptive statistics of annual suspended sediments

6.3.2.1.1 Relationship between suspended sediment concentration and stream discharge There was a strong relationship between the higher rate of discharge and the concentration of sediments that was observed in the tree plantation, bushland, forest and wetland cover types. The relationship was also in line with the stage of the river because the downstream section had relatively higher concentration of sediments compared to the upstream (Figure 6.4).

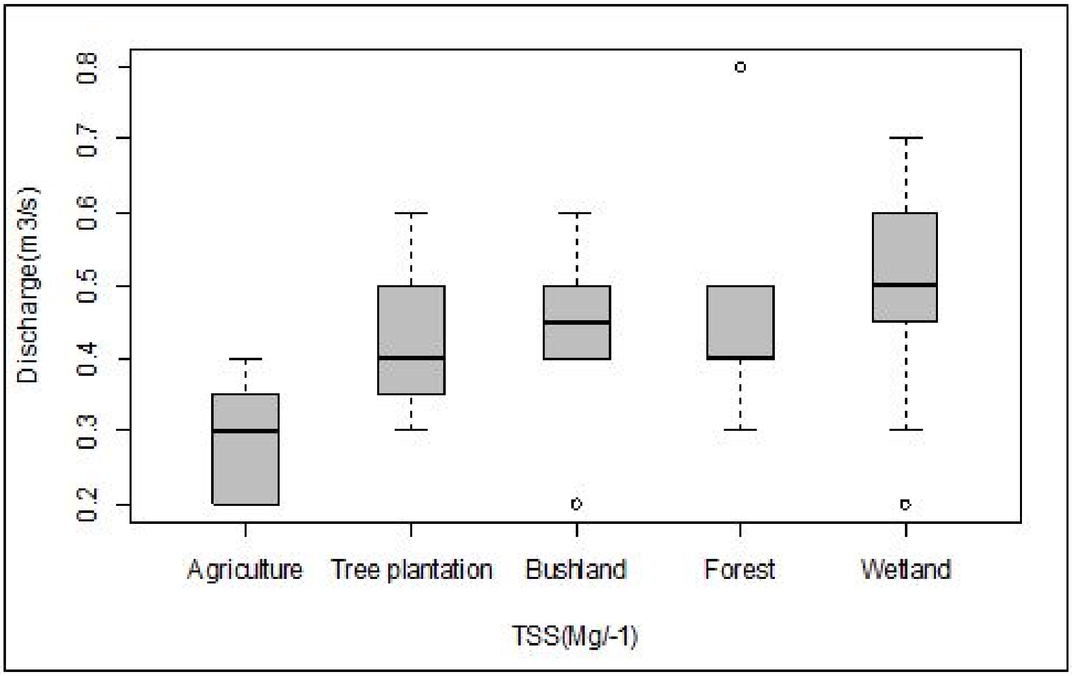

Figure 6.4: Suspended sediment in relation to discharge

6.3.2.2 Stream hydrodynamics

The concentration of the suspended sediments was also closely related to the stream depth, width and discharge. This study shows that the channel morphological parameters had the most significant influence on the concentration and distribution of suspended sediments in the catchment from the sampled land use and cover types (Figure 6.5).

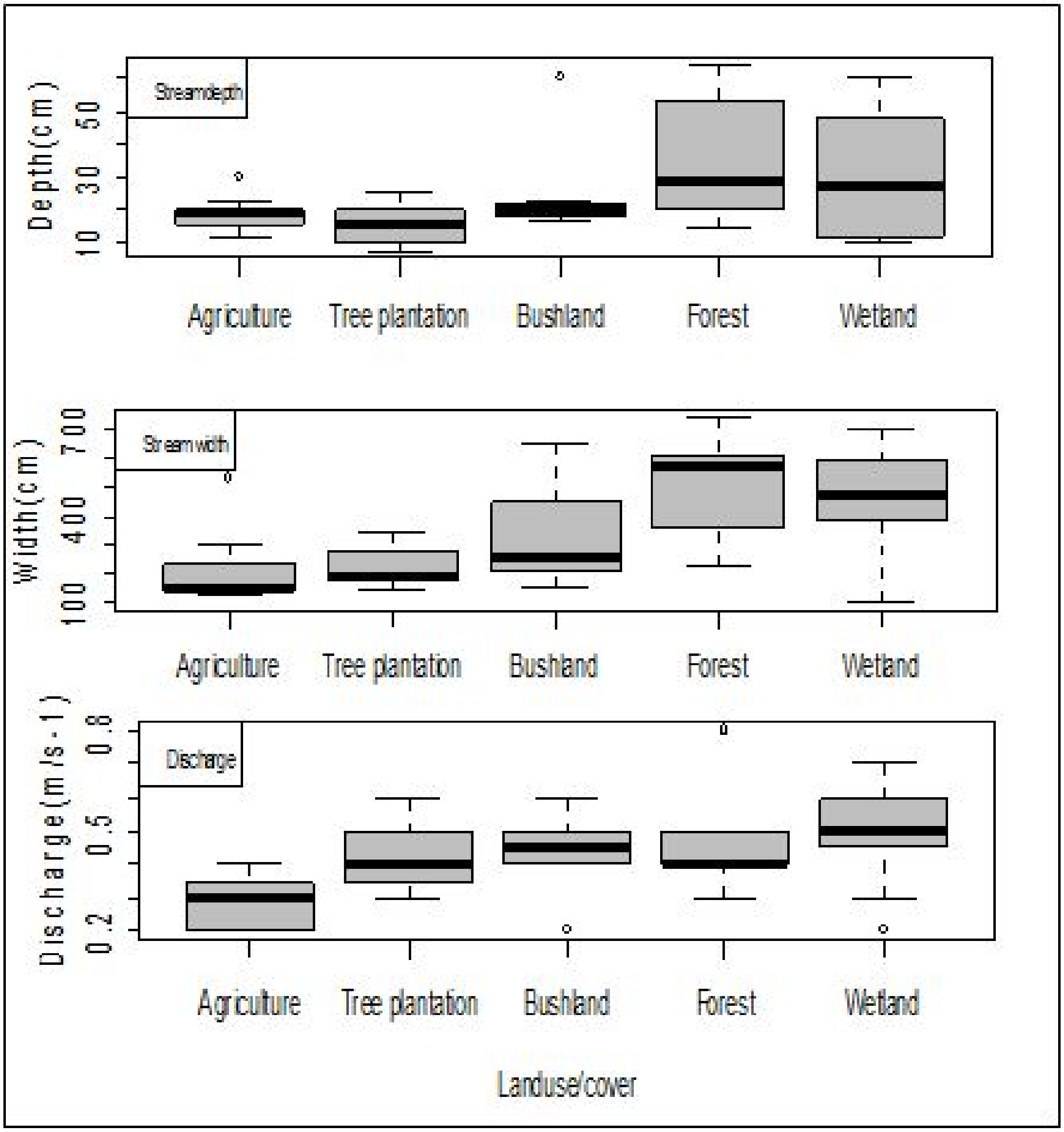

Figure 6.5: River hydrodynamic parameters in relation to land use and cover types

The streamflow hydrodynamic parameters (discharge, stream depth and width) in relation to sediment concentrations had the most significant contributions to the narrowing and widening of the river channel morphology ($P<0.05$) (Table 6.2). However, the stream width (R^2 =0.5) had a much higher contribution than stream depth, and discharge on the river channel aggregation and degradation (Table 6.2).

	TSS (Mg l^2)	Discharge (m^3 /s)	Depth (cm)	Width(cm)
R^2	0.312	0.452	0.426	0.535
F	1.332	2.415	2.174	3.376
Pr >F	0.225	0.012	0.023	0.001

Table 6.2: Values from the statistical significance of sediment concentration in relation to streamflow hydrodynamics (P<0.05)

6.3.2.3 Composition of channel river bed deposit

The principal component analysis results revealed that fine sand (0.25 mm), silty sand (1 mm) and silty clay (0.125 mm) were the most predominant river bed deposit types of particle sizes that dominated the channel bed from the sampled land use and cover types in the catchment. The classified river bed deposit particle grain sizes determined the concentration of bed deposit materials and transport and streamflow from the sampled streams.

6.3.3 River bank stability

The river banks, bulk density were generally low from the sampled land use and cover types. The tropical forest-fully stocked (1.9 Mg/m^3) had the highest amount of bulk density, while the wetland cover type (1.6 Mg/m^3) had the lowest amount. This study reveals that the tree plantation (cohesion=12, angle of internal friction=27) and bushland (cohesion=14, angle of internal friction=22) land cover types had the most stable river banks compared to the sampled land use and cover types (Table 6.3).

Land use	Bulk density	Normal stress	Shear strength	Cohesion	Angle of internal friction	Landscape slope classification (%)
	Mg/m^3	δ_s	t_s	C(kPa)	$\Phi(Degree)$	
Tropical High Forest	1.9	34.1	33.1	8	37	2 (Very gently sloping)
		47.7	43.6			
		74.9	63.8			
Wetland	1.6	34.1	31.7	2	41	7 (Sloping)
		47.7	44.3			
		74.9	67.4			
Tree plantation	1.8	34.1	29.1	12	27	6 (Sloping)
		47.7	36.4			
		74.9	49.9			
Bushlands	1.8	34.1	27.7	14	22	3 (Gently sloping)
		47.7	32.7			
		74.9	44.3			
Agriculture	1.8	34.1	16.2	4	19	4 (Gently gently sloping)
		47.7	19.2			
		74.9	30.1			

Table 6.3: The soil quality parameters from the sampled land use and cover types

6.3.3.1 Soil and root abundance assessment

At the soil profile level, bulk density and root abundance were relatively higher in the first soil horizon A than in the sub-soil layer (horizon B) across the sampled land use and cover types along the channel. The biggest number of root sizes was 6 mm (coarse) and 4 mm (medium), though these were few. However, most of the land use and cover types had roots with the diameter ranging from 0.5-1.5 mm, and these were the commonest especially from the agricultural and wetland land use and cover types (Figure 6.6).

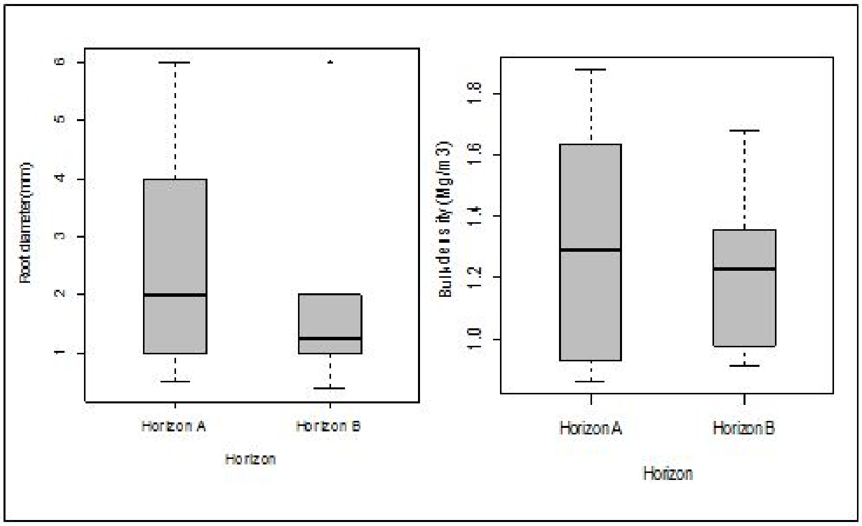

Figure 6.6: The abundance of roots and bulk density as per the soil horizons

6.3.4 Cross sectional geometry

The cross-sectional geometrical assessment revealed that the agricultural land use (crop growing) experienced higher rates of both channel aggradation (0.8 m) and degradation (0.25m) than the channel under tree plantation (Figure 6.7 and 6.8). The right stream bank under the agricultural land use (crop growing) was the most affected bank by aggradation, while under the tree plantation it was the left bank. Subsequently, the goodness of fit statistic showed that the river channel bed slope under the agricultural land use (crop growing) (R^2=0.09) did not influence both channel aggradation and degradation. However, the river channel bed slope under tree plantation (R^2 =0.7) land cover had a strong influence on the stability of both the right and left banks.

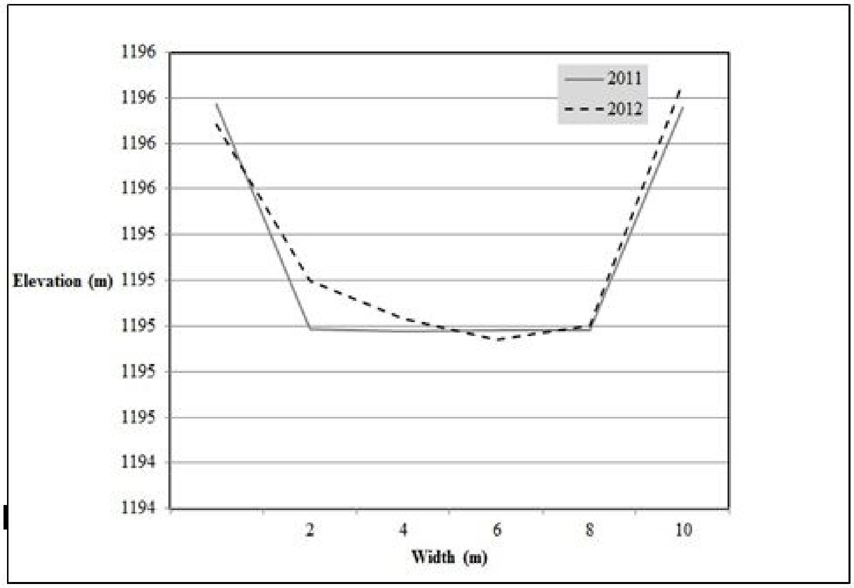

Figure 6.7: A cross–section from the tree plantation land cover

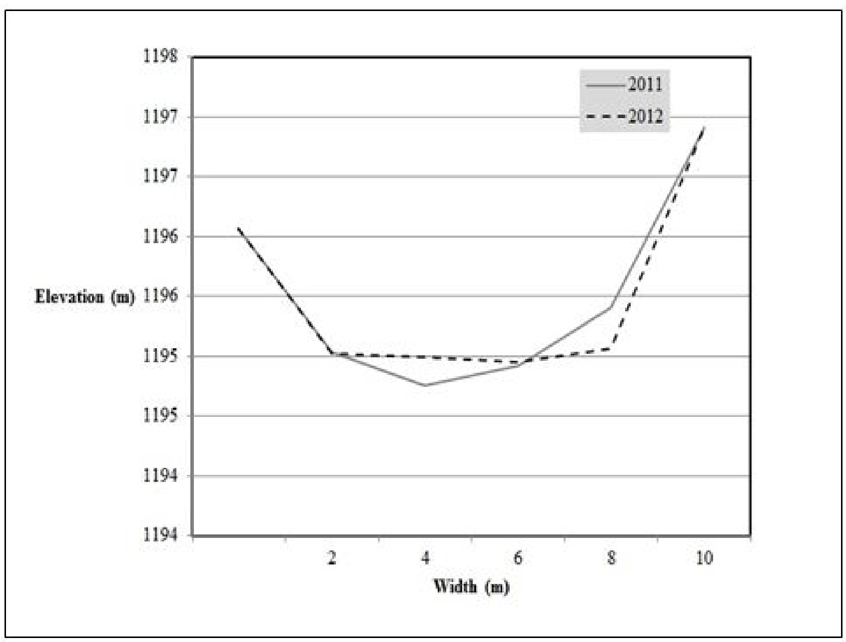

Figure 6.8: A cross section from the agricultural land use

Figure 6.9: River channel degradation (a); and cross–sectional geometrical field survey (b).

6.4 Discussion

This study revealed that the change in river channel planform was reflected in the narrowing and shifting of the channel between 1986 and 2013 in the studied period. The planform occupancy increased because of an increase in the trend of clearing natural streamside vegetation largely to create cultivatable land; and has thus exposed the channel boundary (Murgatroyd and Ternan, 1983; Clark and Wilcock, 2000; Brookes, 2009). VanLooy and Martin (2005) also argued that river channels are very dynamic features in the landscape because they respond rapidly to changes in environmental factors such as climate and anthropogenic change. The narrowing of channel was also attributed to sediment loading from runoff and bank erosion. This is also in agreement with Katz *et al.* (2005) who also argued that this normally happens in the maintenance of a quasi-equilibrium between water and sediment discharge and thus the channel form are accomplished primarily via the adjustment of hydraulic characteristics such as width, depth, velocity, roughness, slope and channel pattern.

The highest concentration of suspended sediments was recorded from the wetland, bushlands, tree plantation, tropical forest and agricultural land use. This study also showed that the higher the discharge rates the higher the concentration of suspended sediments from the sampled land use and cover types. The highest rates of streamflow in the downstream were a result of road construction that led to the diversion of water from small tributaries that originated from the Busitema central forest reserve into one channel. The rates were also supplemented by sediment loading that was caused by rainfall-runoff transported along the road channels. This finding also relates to the results of Shi and Zhang (2005) and Coco *et al.* (2006) who reported that wetlands, which are normally in the floodplains and thus represent a major sediment sink in many drainage basins.

The presence of sand particle sizes along the channel bed was caused as a result of overland rainfall-runoff from the upland areas and in-stream hydrodynamics. This demonstrates the characteristic of the catchment soil composition. This gravel-to-sand transition and associated modifications in channel form were induced by a break in valley slope and an increase in bank resistance from the cohesive bank material. Similarly, Darby and Thorne (2000) and Yang *et al.* (2001) also noted that sand on the riverbed is influenced by river discharge as well as catchment hydrodynamics. In addition, the channel morphological parameters (depth, width, and discharge) had a significant impact on the concentration of suspended sediments in the catchment from the sampled land use and cover types. The simultaneous reductions in channel slope, bed sediment size, and width-to-depth ratio (Webster 2007; Labbe *et al.,* 2011) indicated that the channel crossed a geomorphic threshold to maintain continuity in sediment transport. Larned (2000) also found out that the patterns of retention, transport and processing of riparian detritus in streams are closely related to discharge. The parameters determined the channel variability of sediments, which in turn governed the channel morphology. This variation of sediment concentration was also noted by Montgomery and Buffington (1998) who argued that even a temporal variation in sediment concentration and supply may also influence channel form.

The tree plantation (cohesion=12, angle of internal friction=27) and bushland (cohesion=14, angle of internal friction=22) land cover types had the most stable river banks compared to those under wetland and agricultural land use (crop growing) and cover types. This was attributed to the weathering and weakening processes that reduced the shear strength of the river bank material and the detachment of particles in cohesive soils (Rinaldi and Casagli, 1999) due to stream bank erosion. This is also similar to the findings of Thorne *et al.* (1996) who observed that the type and density of riparian vegetation (grasses, shrubs or trees) are known to stabilize stream bank stability and stable channel form. The cause of aggradation from the agricultural land use (crop growing) was largely attributed to bank erosion. The channel geometry had been weakened by the continuous practice of cultivating land up to the stream boundary, clearing and burning of streamside natural vegetation. Allan (2004) also noted that channel morphology may be influenced by valley slope and confinement, bed and bank material, and riparian vegetation, as well as by the supply from up-slope of water, sediments and wood.

The right bank under the agricultural land use (crop growing) was the most affected bank by aggradation, while from the tree plantation it was the left bank that was affected. The channel aggradation from the tree plantation was a result of livestock trampling of the stream bank in search of drinking water. The aggradation increased the rates of in-channel sedimentation that reduced the water depth and diversion of the river course. This finding was also observed by VanLooy and Martin (2005) who reported that channel changes and growth in the riparian vegetation and livestock rearing may cause a reduction in annual peak flows. Therefore, there is a necessity for controlling livestock grazing to improve the channel condition (Smith *et al.*, 1993).

At the catchment scale, the main drivers of channel morphology were; floods (surface and bank erosion), farming practices such as burning, urbanisation, livestock rearing, industrialisation, and nature of channel morphology among others. Barasa *et al.* (2013) noted that the frequency of extreme events (droughts and floods) over the catchment had reduced from a 4-10 year period to a 1-3 year period. This, therefore, meant that the catchment channel morphology is bound to face an increase in both aggradation and degradation rates. This is because there is an increase in the frequency for floods. The expansion in the area of impervious surfaces was attributed to the urbanization of Busia municipality that increased the in-stream-channel widening. A change in the urban land use was responsible for the reduction in both surface storage and roughness (Friedman and Lee, 2002; McCuen, 2002). This increased the runoff rates and depth. This finding is also in regard to the findings of Montgomery and Buffington (1998) who reported that large impervious surfaces are directly connected to channel networks through drainage channels and thus results into channel widening. The channel is also under pressure from the effluent, which is discharged by the tannery factory into the stream on a daily basis.

6.5 Conclusion

This study stresses that the modification of natural streamside vegetation is responsible for the variations of streamflow through stream bank erosion and channel aggradation and degradation. The study also showed that the higher the discharge rates the higher the concentration of suspended sediments from the sampled land use and cover types. The concentration of suspended sediments was much higher from the wetland cover type. The tree plantation and bushland land cover types had the most stable river banks compared to wetland and agricultural landuse and cover types. The channel morphological parameters (stream depth, width, and discharge) also had a significant impact on the concentration of suspended sediments. The agricultural land use (crop growing) experienced the highest rates of both channel aggradation and degradation than the channel under tree plantation. This study strongly affirms that the stability and instabilities of the river channel geometry had significant impact on the variation of sediment concentration and catchment streamflow. This chapter focused on the effect of land use and cover change on the river channel morphology and their implications for streamflow and sediment concentration.

The subsequent chapter assesses the effect of land use and cover changes on the streamflow of the Malaba River Catchment, Eastern Uganda. This chapter integrates the data/information obtained from the previous chapters which is included/ used in hydrological response modeling of land use and cover changes.

Chapter 7

The effect of land use and cover changes on the streamflow of the Malaba River Catchment, Eastern Uganda

Abstract

The hydrological cycle over most catchments is influenced by changes in land use and cover. This study assessed the effect of land use and cover changes on the streamflow of the Malaba River Catchment using a spatially distributed SHETRAN hydrological model. The calibration period was 1995-1998, while 2009-2012 was the validation period. The study results showed that the highest change in the gain of land was mainly experienced from the agricultural land use (crop growing) (36.7%) and tropical forest-regeneration (2.2%); while the highest loss in land was experienced from the wetlands (24.6%) and bushlands and thickets (15.3%) land cover types. The calibration period had a Nash-Sutcliffe Efficiency (NSE) of 0.78 and validation (NSE=0.81) which showed satisfactory fits between measured and simulated discharge. Therefore, the agricultural land use and tropical forest cover options were the major contributors of streamflow to the Malaba River.

Key words: Land use and cover, streamflow, SHETRAN model, Malaba River

7.1 Introduction

Land use and cover changes alter hydrological cycles by affecting evapotranspiration, soil infiltration capacity, and surface and subsurface flow regimes (Niehoff *et al.*, 2002; Hurkmans *et al.*, 2009) depending on the degree and type of ground cover (Fohrer *et al.*, 2001). The modification in turn affects the water quality and quantity (Roberts and Crane, 1999; Qi *et al.*, 2009) rainfall-runoff volumes, and soil water content (Dezso *et al.*, 2005; Zhi *et al.*, 2009). The hydrological responses to changes in land use and cover are accelerated by natural (e.g. channel degradation) or human-induced (e.g. agricultural management practices) factors that cause changes in the storage characteristics of catchments (McCuen, 2002). The changes are also results of multiple factors including extreme weather events and climate variability, demographic growth, macroeconomic activities, development policies (Li *et al.*, 2007) and physical characteristics of the catchment (Sullivan *et al.*, 2004). Therefore, carrying out an assessment of land use and cover changes can be a basis for the management and ecological restoration of the catchment (Kashaigili, 2008; Nie *et al.*, 2011).

It is important to note that the rate and extent of changes in land use and cover may differ from one region to another. For instance, in many tropical regions, large scale changes in land use and cover may involve the replacement of the natural vegetation cover with crops or pastures, which disrupts the hydrological cycle by altering the water yield (Marcos *et al.*, 2003). In East Africa, nearly 13 million hectares of forest were lost over the last 20 year period, while the remaining forest is fragmented and continually under threat (FAO, 2010). Elsewhere, in the Comet catchment, Australia, the findings from simple coupled water, energy balance framework suggested that most of the observed changes in the annual streamflow were related to climate variability. However, the period (1971-2007) immediately after forest clearing, the catchment showed an increase in the inter-annual streamflow that suggested a decrease in inter-annual evapotranspiration associated with land use and cover changes mainly attributed to higher than average rainfall linked to the La Nina conditions in the wet 1970s (Siriwardena *et al.*, 2006; Jorge *et al.*, 2012).

The effects of land use and cover changes on the catchment hydrology are dependent on the individual characteristics of the catchment such as climatology, topography, bare rock, land use and cover structure or type of soil (Moran-Tejeda *et al.,* 2010). Therefore, investigating the effects of land use and cover changes on the catchment hydrology is vital to inform water and land use managers on the various dynamics causing variations in the catchment streamflow (Beven, 2001; Woonsup and Brian, 2008; Mango *et al.,* 2011). Examining the effect of land use and cover changes on the hydrological cycle continues to be an active area of research within hydrology (Murray 2009). This could be attributed to the improvement in the detection of land use and cover changes across large catchments with the application of remote sensing and geographical information systems techniques (Nutchanart and Wisuwat, 2011). Additionally, carrying out a quantitative analysis of how changes in land use and cover affects the water balance and hydrological cycle is still inadequate in the field of hydrological research in respect to streamflow (Overgaard *et al.,* 2005). Also, observational studies on the effects of land use and cover conversions on the hydrology of medium sized catchments ($>$3,000 km^2) are scarce, especially in the tropics and still, most hydrological studies do not quantify the contributions of individual land use and cover changes on the hydrological components (Nie *et al.,* 2011).

To address this inadequacy, there are numerous well known general hydrological models currently developed and utilized worldwide to investigate the effects of land use and cover changes on the hydrology; and over 20 hydrological models have been listed, synthesized and reviewed by Vijay and Woolhiser (2002) and Isik *et al.* (2012). Hydrological modelling is perhaps one of the means to study the individual and combined effects of multiple factors on the hydrology of large and medium catchments (Qi *et al.,* 2009; Elfert and Bormann, 2010). Therefore, the purpose of this study was to assess the effect of land use and cover changes on the streamflow of the Malaba River Catchment.

7.2 Materials and Methods

7.2.1 Description of study area

Malaba River is a perennial river that is situated on the eastern part of Lake Kyoga (ILM, 2004). The Malaba River is a mid-sized catchment, and transboundary in nature. The catchment is under the Lake Kyoga Management Zone delineated by the Ministry of Water and Environment, Uganda. The river originates from the slopes of Mount Elgon, from where it forms the border between Uganda and Kenya (Lakimo, 2004; Kizito and Ngirane-Katashaya, 2006). The size of the catchment is 2,232 km^2 . About seventy percent of the river is situated in Uganda (midstream and downstream), while the remaining portion is in Kenya (upstream) (Figure 7.1). The catchment experiences a mean annual temperature of about 27.9 °C. The highest precipitation is received between March to May (280 mm/month, 240 mm/month) and August to November (183 mm/month, 170 mm/month). The driest months are January (71 mm/month) and July (81 mm/month). The potential evapotranspiration rates are highest in the months of January (148.8 mm/month) and March (148 mm/month). The lowest are experienced in the months of May, June, July, and August with 114 mm/month respectively. The major soil types in the catchment fall under a soil catena group of, Petric plinthosols, and Gleysols. The other soil types are under Lixic ferrasols, Acric ferrasols and Nitisols. These soil catena groups can be distinguished easily because they represent earlier stages of the weathering processes (NEMA, 1997).

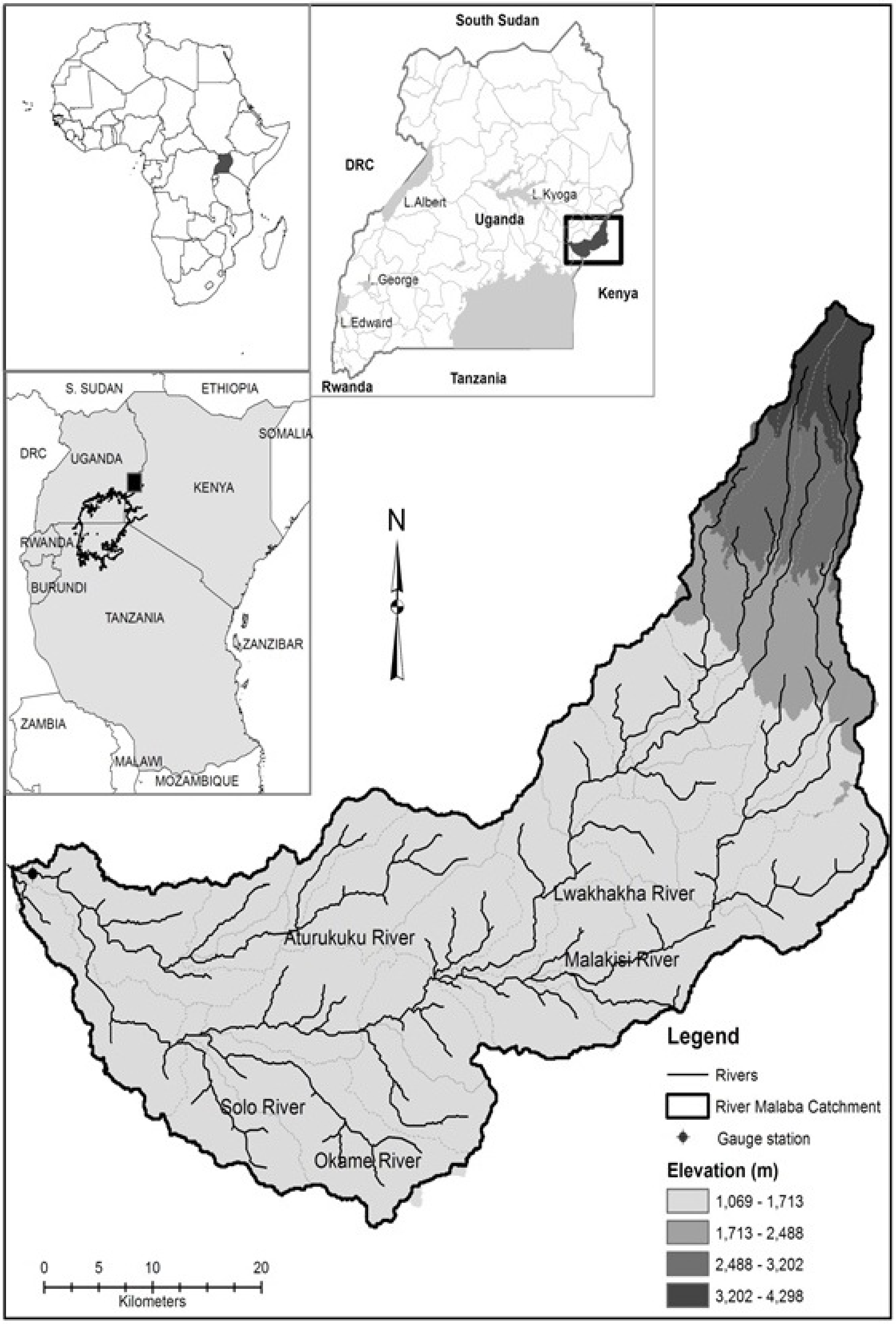

Figure 7.1: The Malaba River Catchment

7.2.2 Modelling approach

A physically based distributed SHETRAN model was used to assess the effect of land use and cover changes on the streamflow, while a multiple regression analysis was carried out to establish the relationship between land use/cover and streamflow. The approach was based on the fact that the effects of land use and cover changes in hydrology are twofold: (i) on the overall water availability or the mean annual runoff and (ii) on the seasonal distribution of water availability (Kiersch, 2000).

7.2.3 Description of the SHETRAN hydrological model

SHETRAN (version 2.101) is a physically-based, distributed, deterministic, integrated surface and subsurface modelling system, designed to simulate water flow, sediment transport, and contaminant transport at the catchment scale (Ewen *et al.*, 1995; Birkinshaw *et al.*, 2010). The water flow component is an updated version of the System Hydrologique European (SHE) (Abbott *et al.*, 1986a, 1986b). The sediment component is an updated version of SHESED (Wicks, 1996), and the scientific basis of the contaminant transport component is given in Ewen (1990); and Purnama and Bathurst (1991). Flow is assumed not to be affected by transport and sediment transport not to be affected by solute transport, so the three components lie in a natural hierarchy (Ewen *et al.*, 2000; Beven, 2002; Adams and Elliott, 2006). Additional theoretical description of the SHETRAN model, flow equations appropriate for this study, and its capabilities are presented in detail by Ewen *et al.* (1995) and Bathurst (2002).

7.2.4 Relationship between land use/cover changes and hydrological components

A multiple regression analysis was carried out to assess the relationship between land use and cover changes and hydrological components (streamflow, evapotranspiration, rainfall) in the studied hydrological period (1995 and 2012). The multi col-linearity correlation was carried out to determine the relationship amongst the hydrological components. The analysis was carried out at a catchment scale where the independent variables were the land use and cover classes (i.e. Tropical forest fully stocked and Regeneration, Bushlands and thickets, Agriculture-non uniform, Wetlands, Built up and open water). The dependent variables (responses) were the hydrological components (i.e. streamflow, precipitation, and evapotranspiration). The relationship was defined using the R-squared values obtained from the multiple partial regression analysis. However, the municipal water abstraction data were not included in the study because of data inaccessibility and consistency.

7.2.5 Model data preparation, application and analysis

7.2.5.1 Hydro-meteorological data and analysis

The obtained meteorological (rainfall and evapotranspiration) data from the two stations and streamflow datasets were analysed using double mass curve procedures to check for (Figure 7.2) data inconsistencies (Rugumayo and Mwebaze, 2002).

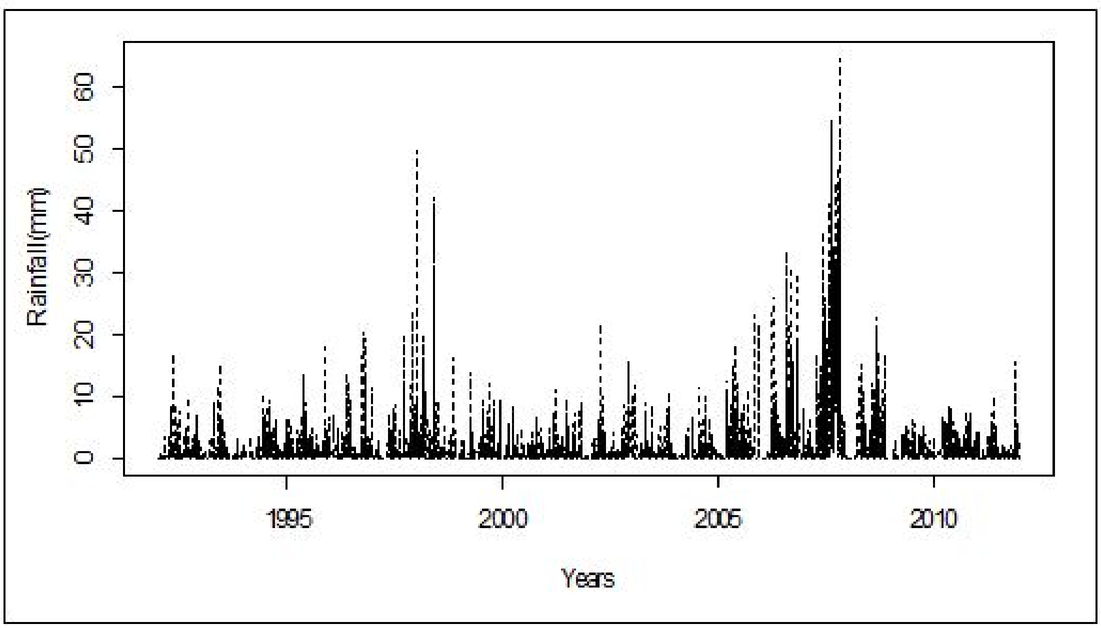

Figure 7.2: Precipitation for the 1992-2012 period (downstream station)

7.2.5.2 Changes in precipitation

An inter-decadal assessment of rainfall records was carried out to assess the rainfall changes in the Malaba River catchment. A non-parametric Sen' estimator methodology was adopted to determine the magnitude of rainfall trend in the catchment.

The linear model *f(t)* is described as expressed by Sen (1968) as:

$$f(t) = Qt + B \quad (1)$$

Where Q is the slope, B is a constant

To derive an estimate of the slope Q, the slope of all data pairs were calculated

$$Q_i = \frac{X_j - X_k}{j - k}, i = 1,2,....N, j > k \quad (2)$$

Where *xj* and *xk* are data values at time *j* and *k(j>k)* respectively. The median of these N values of Ti is Sen's estimator of slope which was calculated as:

$$\beta = \left\{ \frac{1}{2}^{T_{\frac{N+1}{2}}} \left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}} \right) \right\} \textbf{N is odd} \quad (3)$$

A positive value of β indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

The significance of changes in annual rainfall was determined with the use of Mann-Kendall and Distribution free CUSUM non parametric tests. These were carried out to detect the possible changes in precipitation (increase or decrease). The Mann-Kendall test was adopted to assess changes in precipitation; while the Distribution free CUSUM test was carried out to test whether the data was different for an unknown time of change. The n time series values (X1, X2, X3, . . . , Xn) were replaced by their relative ranks (R1, R2, R3,. . . . ., Rn). The Mann-Kendall test statistic S is given below:

$$S = \sum_{k=1}^{n=1} \left[\sum_{j=k+1}^{n} \mathbf{sgn} \left(R_i - R_i \right) \right] \tag{1}$$

Where sgn(x) = 1 for $x > 0$

sgn(x) = 0 for x = 0

sgn(x) = -1 for $x < 0$

if the null hypothesis H0 is true, then S is approximately normally distributed with:

$\mu = 0$

$$\sigma = n(n-1)(2n+5)/18 \tag{2}$$

The z-statistic critical test for various significance levels

$$Z = |S|/\sigma 0.5 \tag{3}$$

A positive value of S connotes an "upward trend", while a negative value of S indicates a "downward trend"(Partal and Kalya, 2006; Karpouzos *et al.*, 2010). In this analysis, the null hypothesis was tested at 95% confidence level.

And for the Distribution free CUSUM test given a time series data (x1,x2,x3,. . . . . . , xn), the test statistic is defined as

$$Vk = \sum_{i=1}^{k} \mathbf{sgn}\ \left(x_i - x_{median} \right) k = 1,2,3............n \tag{4}$$

Where sgn(x) = 1 for $x > 0$

sgn(x) = 0 for x = 0

sgn(x) = -1 for $x < 0$

Xmedian is the median value of the x1 data set

The distribution of Vk follows the Kolmogorov-Smirnov two-sample statistic (KS = (2/n) max |Vk|) with the critical values of max |Vk| given by:

α = 0.10 1.22$\sqrt{n}$

α = 0.05 1.22$\sqrt{n}$

α = 0.01 1.63$\sqrt{n}$

A negative value of Vk indicates that the latter part of the record has a higher mean than the earlier part and vice versa.

7.2.6 Disaggregation of Rainfall and Evapotranspiration data

The hourly precipitation data is a requirement for simulation of the SHETRAN Model (Birkinshaw *et al.,* 2010). Therefore, the hyetos model was used to disaggregate the obtained daily rainfall into hourly data based solely on a temporal stochastic disaggregation scheme (Jose *et al.,* 2003). The Bartlett-Lewis rainfall model was applied as a background stochastic model for rainfall generation. The model uses a repetition scheme to derive a synthetic rainfall series, which resembles the given series at the daily timescale and subsequently, the proportional adjusting procedure, to make the generated hourly series fully consistent with the given daily series (Koutsoyiannis and Manetas, 1996; Debele *et al.,* 2007). The model was chosen because of its wide applicability in several climatic regions (Koutsoyiannis and Onof, 2001). Figure 7.3 below shows the marginal statistics between the disaggregated and original precipitation data. The variation was acceptable for the data to be incorporated into the hydrological model. The daily evapotranspiration data were disaggregated into hourly data with the use of a climatic tool (Daily to hourly PET) in the System for Automated Geo-scientific Analyses (SAGA) software. The tool was appropriate given the daily precipitation and evapotranspiration data which was available for the catchment.

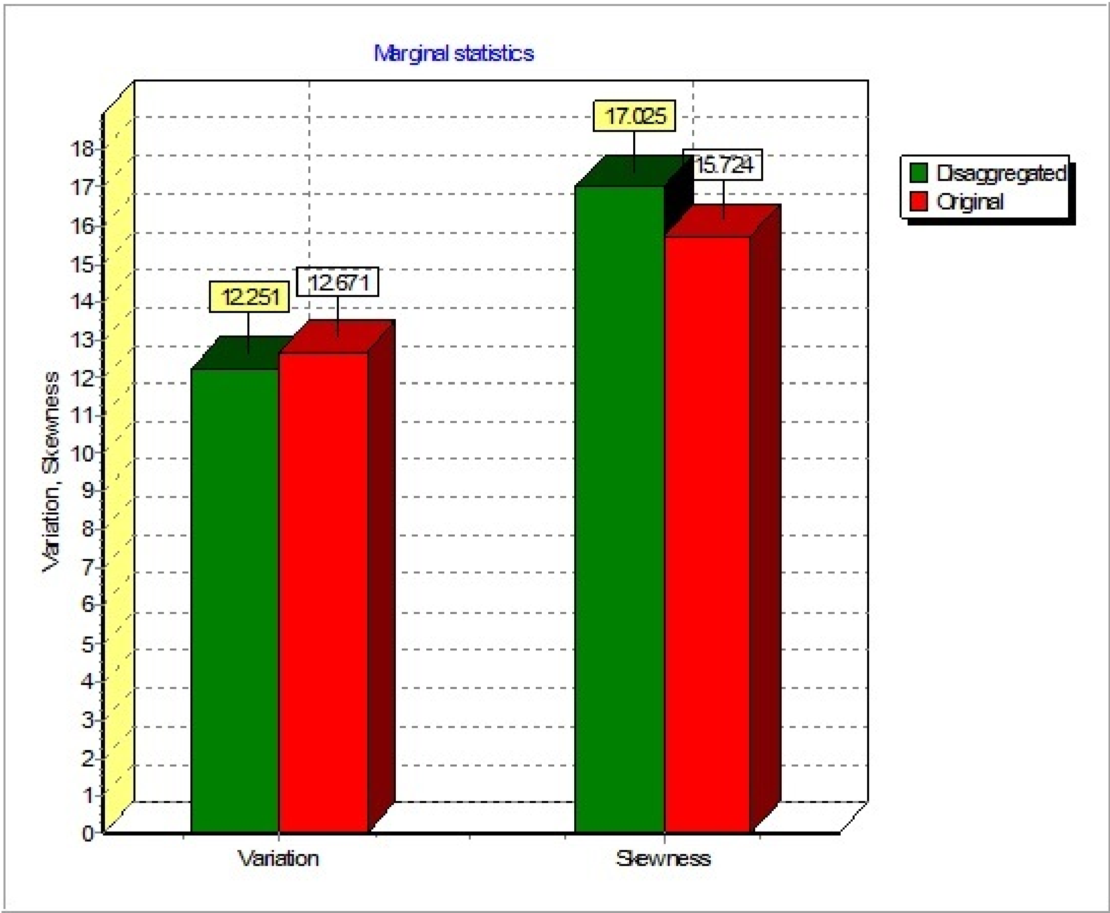

Figure 7.3: Marginal statistics of disaggregated data

7.2.7 Quantification of the land use and cover changes

The study utilized two sets of multi-temporal, cloud free (0%) and ortho-rectified Landsat TM/ETM+ (30 m) imagery of 1995 and 2012; (Path 170 row 59; Path 170 and row 60 under PCS WGS 1984 UTM, zone 36N) to quantify the extent of land use and cover changes in the catchment. The images were appropriate for land degradation assessment. The images were pre-processed using a 3 x 3 majority filtering method prior to classification (McDonnell, 1981; Cleve *et al.*, 2008). The pre-processed images were classified following supervised classification procedure (Maximum Likelihood) because each land use and cover class had a Gaussian distribution (Dewan and Yamaguchi, 2009).

The study adopted the National Biomass Study (2003) land use and cover classification scheme for the description of land use and cover classes in Uganda. The study comprehensively classified land use and cover types/classes in the country. The classified images were validated with the use of ground truthed data for accuracy assessment. The redefinition of the each spectral class into a land use type was based on the results obtained from ground truthed data. In addition, the land use and cover map of 2003 in the eastern region (Uganda) created by the National Biomass Study (2003) was obtained and used as a reference in the image classification process. The classified land use and cover classes included woodland, tropical forest (fully stocked), tropical forest (regeneration), bushlands and thickets, agriculture (non-uniform), wetland (permanent), built up areas, and open water.

An error matrix algorithm was adopted for image accuracy assessment in accordance to the procedures as suggested by Foody (2002). The final classified maps were cross-tabulated to examine the gains and losses of land use and cover changes (Shalaby and Tateishi, 2007). To establish the most significant drivers of land use and cover changes, three focus group discussions were conducted in the midstream and downstream sections of the catchment (Hollingshead, 1996). These gave a moderate representation of population in the catchment.

7.2.8 Topographical and soil data

Topographically, a 90m Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was obtained (http://srtm.csi.cgiar.org/) and utilized to derive information about the morphology of the catchment land surface (Jenson, 1991; AntoniĂŚ *et al.*, 2001). The DEM was pre-processed using the fill the sinks (Planchon and Darboux, 2001) procedure of rounding of elevations to the nearest integer value in a GIS environment (Tarboton *et al.*, 1991; Kenny *et al.*, 2008). The study acquired and extracted the soil map for the area of study using the FAO soil map of Africa was (FAO, 2002). However, the soil map was refined to a more detailed and moderate scale prior to its incorporation into the SHETRAN hydrological model. The defined soil classes and parent material type were further reclassified using a more comprehensive and high resolution soil maps for both Uganda and Kenya.

The study laid out field plots (50 x 50m) that were measured 100m away from the river channel where soil composites were randomly sampled from the representative land use and cover types (agriculture, tropical forest, regenerating forest, bushlands, tree plantation, and wetland). The sampling was carried out at two soil depths, i.e. 0-15cm and 15-30cm. The collected soil samples were analysed for physio-chemical properties in the laboratory following Okalebo *et al.* (2002) laboratory methods for soil analysis. A series of double ring soil infiltration experiments were conducted from the representative land use and cover types. This approach was adopted because water infiltration is an important component of catchment water balance. The double ring technique was chosen because it minimized the slacking effect and the effect of lateral water flow (Achouri and Gifford, 1984; Bamutaze, 2010).

7.2.9 Model application

SHETRAN model version 2.101 (GUI) was set up and incorporated with disaggregated daily to hourly rainfall and evapotranspiration data to simulate discharge in the both the calibration and validation periods. In addition, the DEM, mask, soil and land use and cover datasets were re-sampled to a 50 X 50 m grid cell size as a requirement for the model prior to their incorporation in the model. For vegetation, canopy storage capacity, leaf area index, maximum rooting depth (m) and AE/PE at field capacity. The soil water retention and hydraulic properties for each soil layer were derived from texture, bulk density and organic matter content values using the methods of Brooks-Corey and Van Genuchten (Rawls and Brakensiek, 1989). Direct measurements of leaf area index and rooting depth were obtained from previous DHSVM studies (Bowling and Lettenmaier, 1997) and from the Land Data Assimilation System (LDAS).

The SHETRAN model processes, assumptions and calculations that governed interception, actual evapotranspiration, transpiration, generation of runoff, overland flow, erosion by rainfall, transport capacity were described following the procedures and equations as described and presented by Abbott *et al.,* (1986); DeFigueiredo and Bathurst (2001); Anderton *et al.,* (2002). However, the model was parameterized, using field data and functions that required little and cheaply obtained information prior to simulation.

7.2.10 Calibration and validation

The rainfall, discharge and evapotranspiration datasets were separated into two time periods between 1995-1998 and 2009-2012 over the catchment. The two periods were selected for model calibration and verification. Validation was necessary to improve the predictive capacity of the model. This validation period represented a combination of dry, average and wet years. The four year period was chosen because the physically based distributed models tend to be very computationally expensive and impractical for use in very long-term simulations (Sloan and Ewen, 1999). During calibration, the split-sample test was carried out to determine the goodness of fit of the model (land use and cover) and validation on periods with different conditions (KlemeÂš, 1986). Therefore the model was run for 8 years.

The model was manually calibrated against the available discharge data. The principal calibration parameters were soil conductivity, the overland flow resistance coefficient and evapotranspiration parameters. There was no formal criterion set for the calibration goodness of fit, but the process aimed to improve the Nash-Sutcliffe efficiency due to the variations in soil types, depth and vegetation. This was intended to reproduce hydrological responses representative of the principle characteristics of the catchment especially the range of peak discharge and seasonal variations. The 1995 land use and cover map were utilised in the calibration period, while the 2012 land use and cover map in the validation period. However, the soil parameters were assumed to be constant in both the calibration and validation periods.

7.2.11 Nash-Sutcliffe Efficiency

The model performance during calibration was evaluated using two criteria: Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) and simulated hydrograph.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{N} (Yi^{obs} - Yi^{sim})^2}{\sum_{i=1}^{N} (Yi^{obs} - Yi^{mean})^2} \right] 1$$

A value between 0.6 and 0.8 indicates that the model performs reasonably. Values between 0.8 and 0.9 indicate that the model performs very well and values between 0.90 and 1.0 indicate that the model performs extremely well (Nash and Sutcliffe, 1970).

7.3 Results

7.3.1 Quantification of the land use and cover changes

Generally, the catchment has experienced significant changes in land use and cover between 1995 and 2012 period. These changes are reflected in the gains and losses of land covered by different land use and cover types. In 1995, bushlands and thickets and wetland cover types covered a relatively higher percentage of land than the other classified land use and cover types; whereas in the year 2012, agriculture and bushlands and thickets covered the largest portion of land area in the catchment (Figure 7.4 and Table 7.1). The highest gain was experienced from the agricultural land use (crop growing) (36.7%) followed by tropical forest (regeneration) with 2.2%, and lastly from both woodland and built-up land use and cover types. The highest change in the loss of land was largely experienced from wetlands (24.6%) and bushlands and thickets (15.3%). Tropical forest (fully stocked) and open water areas later followed with 1.5% and 0.005%, respectively (Figure 7.4 and Table 7.1). The overall image classification accuracy assessment was 80.4%, while user's accuracy was 98.1% and producer's accuracy at 80.1%.

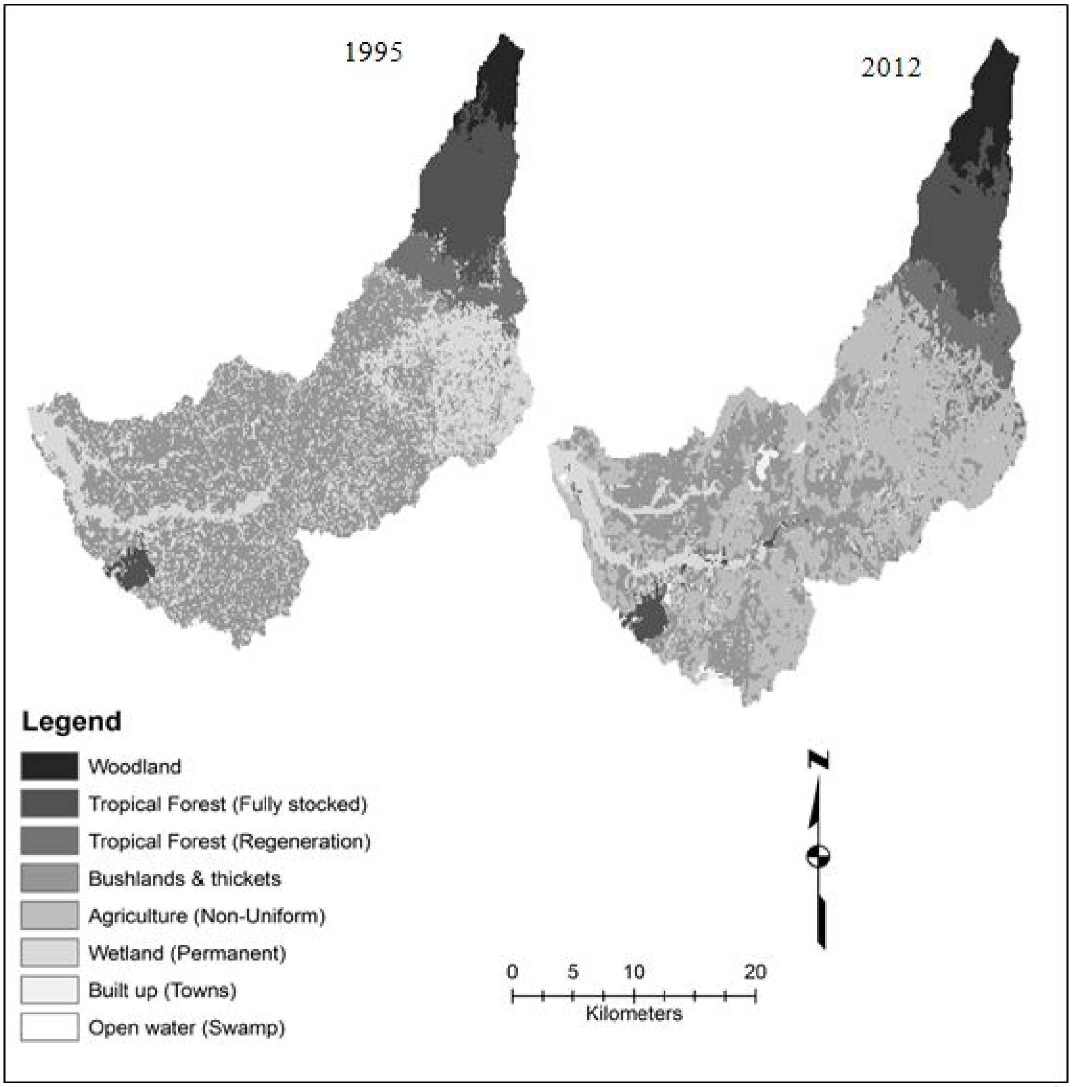

Figure 7.4: Land use and cover changes for year 1995 and 2012

	Period	
	1995	2012
Land use and cover types	**Relative area%**	**Relative area%**
Woodland	3.0	4.8
Tropical Forest (Fully stocked)	12.1	10.6
Tropical Forest (Regeneration)	4.9	7.1
Bushlands and thickets	40.9	25.6
Agriculture (Non Uniform)	6.1	42.8
Wetland (Permanent)	32.8	8.2
Built–up (Areas)	0.1	0.8
Open water (Swamp)	0.04	0.035

Table 7.1: Percentage of land use and cover changes in the 1995–2012

7.3.1.1 Contributors of gains and losses of land use and cover changes

The contributors in the gain and losses of land use and cover changes varied within the classified land use and cover types in the studied period. The cross tabulation results showed that the wetland cover type (179.3%) was the major contributor of land in the increment of agricultural land use type (crop growing). This was followed by bushlands and thickets (83.7%) and lastly tropical forest regeneration with 29.6%. The tropical forest fully stocked was the major contributor of land occupied by woodlands (17.3%) and bushlands and thickets (0.7%). The tropical forest (regeneration) was also the major contributor of land to the tropical forest fully stocked (10.6) and agriculture (3.4%); Bushlands and thickets contributed to the gain in land of agriculture (16.5%), tropical forest (regeneration) (0.9%) and wetland (0.9%). Likewise, the agricultural land use (crop growing) was the main contributor of land to both bushlands and thickets (40%) and wetlands (6.7%). Lastly, the built-up areas contributed more land to bushlands and thickets (3.7%) and agriculture with 2.6% (Table 7.2).

Land use and cover types	%Change Moisture category
Woodland to Tropical forest fully stocked	0.6(+)
Tropical forest fully stocked to Woodland	17.3(+)
Tropical forest fully stocked to Tropical forest regeneration	0.5(+)
Tropical forest fully stocked to Bushlands and thickets	0.7(+)
Tropical forest fully stocked to Agriculture	0.2(-)
Tropical forest fully stocked to Wetland	0.2(+)
Tropical forest fully stocked to Built–up areas	0.1(+)
Tropical forest regeneration to Tropical forest fully stocked	10.6(+)
Tropical forest regeneration to Bushlands and thickets	1.9(+)
Tropical forest regeneration to Agriculture	3.4(+)
Tropical forest regeneration to Wetland	0.1(+)
Bushlands and thickets to Tropical forest fully stocked	0.3(+)
Bushlands and thickets to Tropical forest regeneration	0.9(+)
Bushlands and thickets to Agriculture	16.5(-)
Bushlands and thickets to Wetland	0.9(-)
Bushlands and thickets to Built–up	0.1(-)
Agriculture to Tropical forest fully stocked	0.2(+)
Agriculture to Tropical forest regeneration	2.1(+)
Agriculture to Bushlands and thickets	40.0(+)
Agriculture to Wetland	6.7(+)
Agriculture to Built–up	1.2(+)
Wetland to Woodland	0.4(-)
Wetland to Tropical forest fully stocked	5.2(-)
Wetland to Tropical forest regeneration	29.6(-)
Wetland to Bushlands and thickets	83.7(+)
Wetland to Agriculture	179.3(+)
Wetland to Built–up	1.8(+)
Built–up to Bushlands and thickets	3.7(+)
Built–up to Agriculture	2.6(+)
Built–up to Wetland	0.5(+)
Open water to Wetland	33.3(+)

Table 7.2: Contributors of land use and cover changes between 1995 and 2012 period

7.3.2 Changes in precipitation

Generally, the catchment has experienced an increasing trend in the annual changes in the amount of precipitation received in the studied period. The least downward precipitation trend was only recorded between 1991 and 1994 (Figure 7.5 a and b). The catchment experienced a prolonged variation of received rainfall between 1994 and 2003 period, unlike the later years (2005-2012) where the return peak periods were more frequent (Figure 7.5 b). An upward trend in the annual changes in rainfall received by the catchment is reflected in the positive value of beta estimated by the Sen's estimator at the 95% confidence value (Figure 7.5 c and d). However, the trend in the annual changes in rainfall received by catchment was not significant ($P>0.05$) in the study period. In addition, the earlier years experienced prolonged annual rainfall events than the later years from 2005. There was also no significant difference in the mean annual changes in the rainfall recorded in the catchment (Table 7.3). The temporal variation and intensity in the annual rainfall changes also gave an important insight on the trend of streamflow in the catchment.

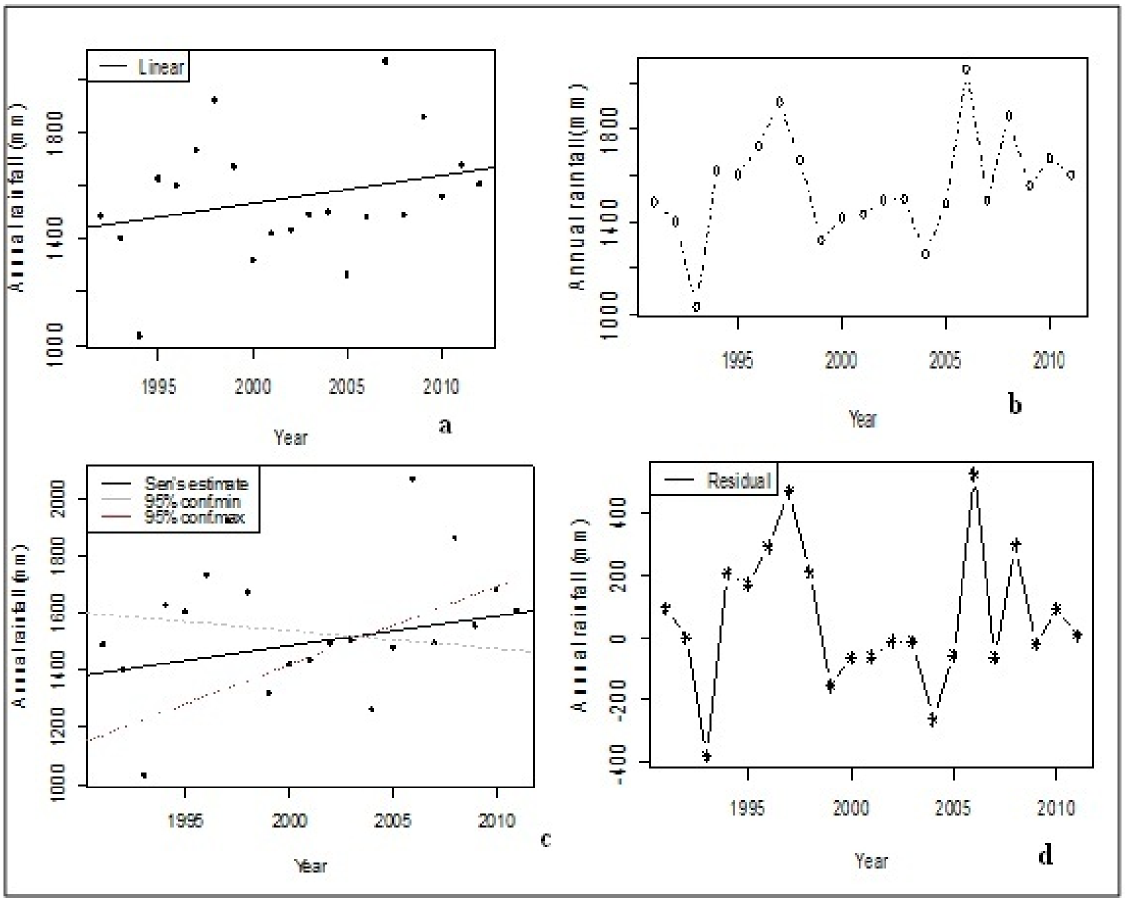

Figure 7.5: Temporal variation (a), trend (b) Sen's slope estimate (c) and residual (d) of annual rainfall(mm) period 1991-2012

Parameters	*Test statistic*	*Critical values*			*Result*
		(statistical table)			
		a=0.1	a=0.05	a=0.01	
Mann–Kendall	1.359	1.645	1.96	2.576	NS
Cusum	5	5.591	6.232	7.47	NS
Auto Correlation	0.989	1.645	1.96	2.576	NS
Sen's slope estimate					
	Q	B	Bmin95	Bmax95	
	10.3	1391.5	1595.48	1175.52	

NS (Not significant at 0.05)

Table 7.3: Sen's slope estimate and significance of annual rainfall trend

7.3.3 Mean variation of the hydrological components

Table 7.4 shows that the annual amount of rainfall and evapotranspiration rates did not increase in the studied period. The runoff coefficient was relatively high in 1995 because of the prolonged and intensive amount of rainfall received than in 2012.

Period	**P (mm/day)**	**Q (m^3/s)**	**Q (mm/day)**	**ET (mm/day)**	**C**
1995	4.65	0.6	8.14	4.08	0.13
2012	4.72	0.5	7.37	4.20	0.11

Table 7.4: The mean hydrological components of the Malaba River Catchment

P is precipitation, Q is discharge, ET is evapotranspiration (P–Q), and C is the runoff coefficient (Q/P)

7.3.4 Streamflow availability between 1995 and 2012

The difference in the streamflow availability in the studied years (1995 and 2012) demonstrated that the catchment flow was not consistent over the catchment. The year 1995 had a prolonged availability of streamflow than in 2012 that occurred between April and October. This study also notes that there was a shift in the length of streamflow availability from the months of April–October in 1995 to August–December in 2012. This finding was in–line with the difference in the streamflow availability experienced from March to September in the studied period (Figure 7.6).

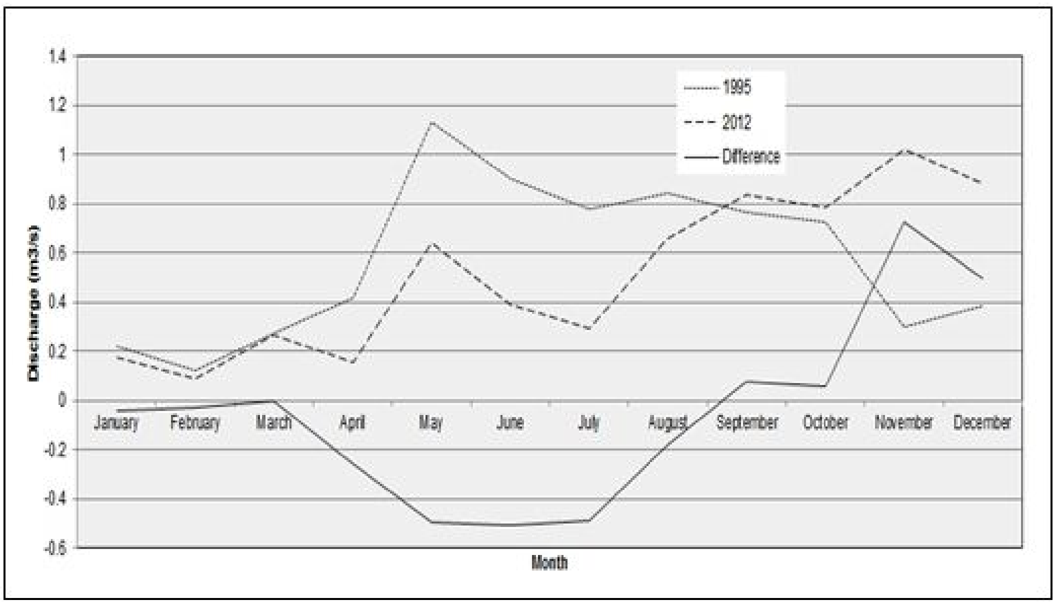

Figure 7.6: The availability of streamflow in the studied years (1995 and 2012)

7.3.5 Seasonal distribution of streamflow availability between the calibrated and validation periods

The seasonal distribution of streamflow availability showed that in the calibration period (1995-1998) the river experienced a high amount of monthly streamflow than in the validation period (2009-2012). The calibration and validation periods showed that the monthly discharge recorded was highest in the months of May (143 m^3/s) and November (118 m^3/s) than in February (18 m^3/s) and July (37 m^3/s (Figure 7.6).

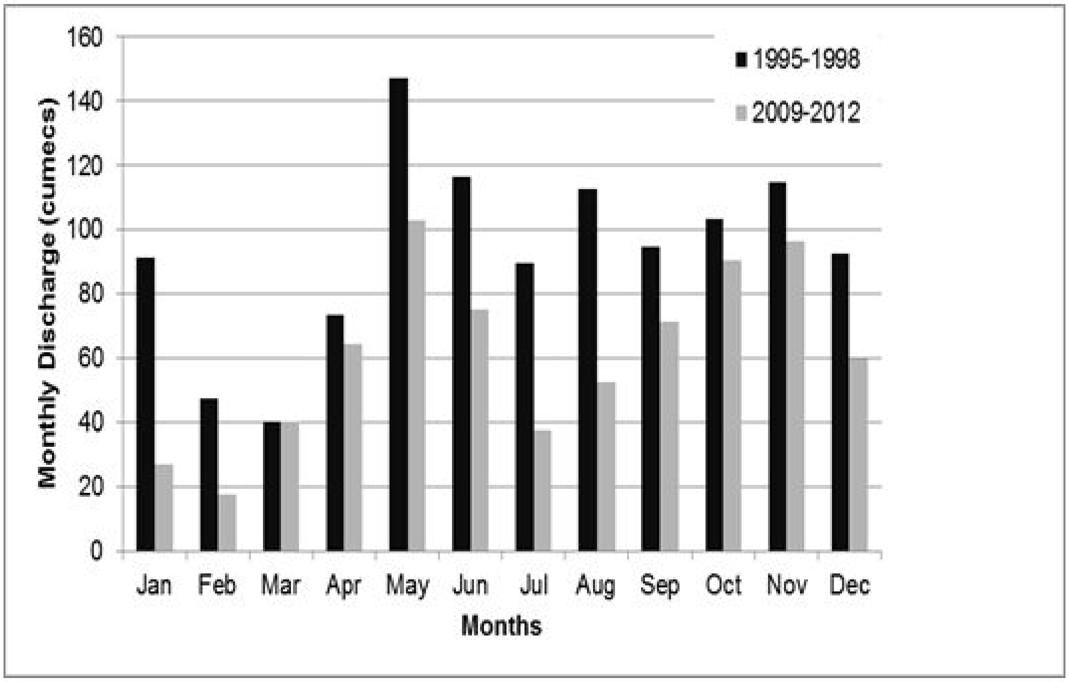

Figure 7.7: Seasonal distribution of streamflow between the calibration and validation periods)

7.3.6 Model results

The calibration (NSE=0.78) and validation (NSE=0.81) periods showed satisfactory fits between measured and simulated discharge in the studied periods (1995-1998 and 2008-2012). The model showed no systematic errors between the high and low flows evident in the validation period (Figure 7.9) unlike in the calibration period (Figure 7.8). The model results suggested that the peak and low flow conditions were largely attributed to changes in the area occupied by agricultural land use (crop growing) and tropical forest in the simulated periods that influenced surface rainfall runoff. In addition, the model results indicated that the catchment hydrological responses to changes in land use and cover were not constant from the experienced rainstorm events that occurred during the studied periods. The overland flow coefficient for the calibration period was 0.02 $m^{1/2}s^{-1}$, while 0.06 $m^{1/2}s^{-1}$ for the validation period (Figure 7.8 and 7.9). The coefficient ranges between calibration and validation periods demonstrated a characteristic of sandy loam soils that cover a large portion of land in the catchment.

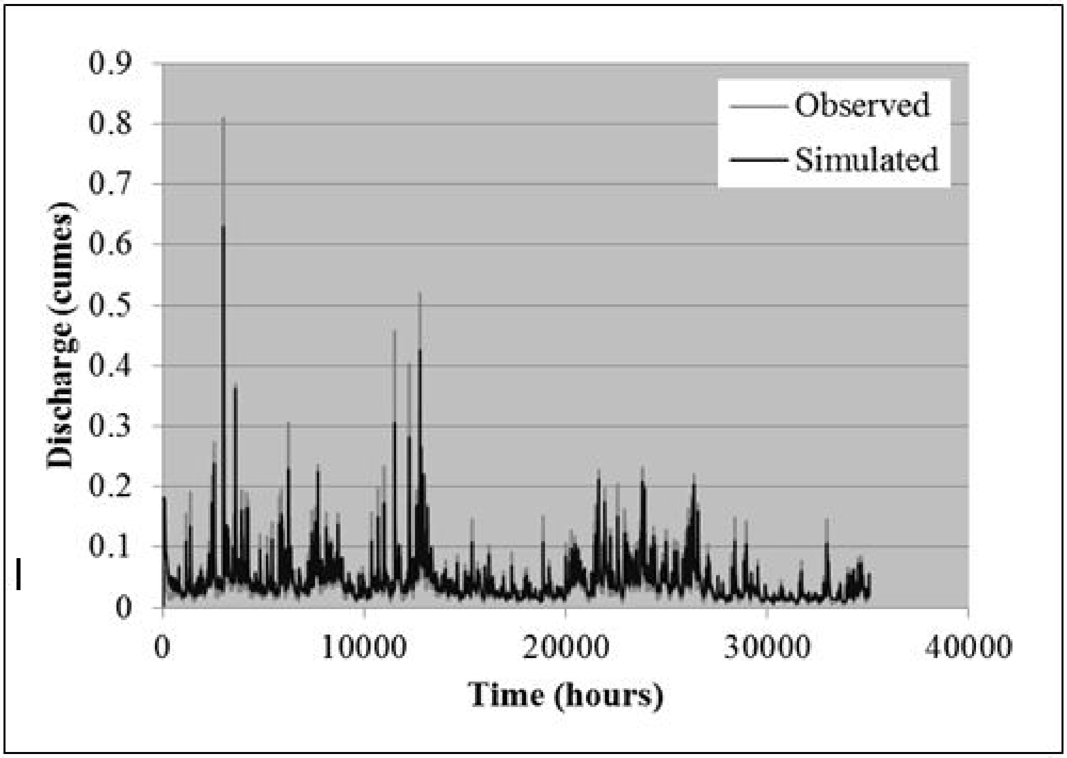

Figure 7.8: Calibration period (1995-1998)

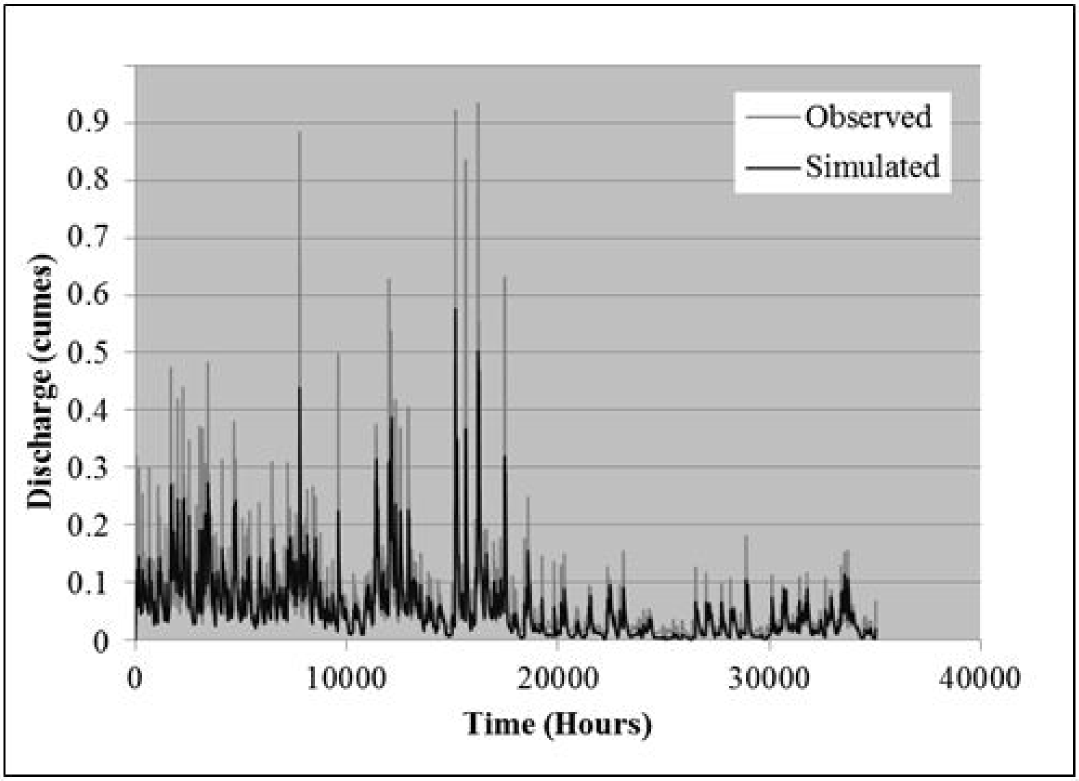

Figure 7.9: Validation period (2008-2012)

7.3.7 Relationship between hydrological components and land use and cover changes

Table 7.5 below shows, the results from multiple regression analysis that indicated that, the woodlands, tropical forest regeneration, agriculture and built-up areas had the highest influence on the hydrological components (streamflow, evapotranspiration, rainfall) in the studied period (1995-2012). However, the agricultural land use (crop growing) influenced the hydrological components more than other land use and cover types. This was because of its large land coverage extent in the catchment. The least influential land use and cover were open water and wetland on the hydrological components.

Table 7.5 Summary of multiple regression of land use and cover type (predictors) with each hydrological component response.

The R-squared are listed with the direction of influence (negative or positive) in the studied period 1995-2012 (Table 7.5).

	Predictors								
Responses	**W**	**TFF**	**TFR**	**BT**	**AN**	**W**	**BA**	**OP**	$\mathbf{R^2}$
Streamflow	+	−−	+	−−	+	−−	+	−−	0.990
PET	+	−−	+	−−	+	−−	+	−−	0.998
Rainfall	+	−−	+	−−	+	−−	+	−−	0.999

Key: **W** =Woodland; **TFF** = Tropical Forest (Fully stocked); **TFR**= Tropical Forest (Regeneration); **BT** = Bushlands and thickets; **AN**= Agriculture (Non Uniform); textbfW= Wetland; textbf BA= Built up areas; **OP** = Open water.

7.4 Discussion

The recorded amount of streamflow was higher and prolonged in 1995 than in 2012. The longer periods of streamflow availability in 1995 were in relation with the recorded prolonged and intensive flood peaks than in 2012, which were contrary but more frequent. This finding demonstrates that there are stronger links between the overall streamflow, and rainfall availability (Johnson and Odada, 1996). There is also a shift in the length of streamflow availability from the months of April - October in 1995 to August - December in 2012 (refer to Figure 7.5). This change in the pattern of streamflow availability from the first quarter to the last quarter of the year coincides with the findings of Kagawa (2009) who also noted a probable change in the rainfall pattern in Uganda. It is important to note that the East African shorter rains (October-December) have a positive correlation with El Nino-Southern Oscillation (Chamberlain, 1995; Mutai and Ward, 2000).

The simulation results indicated that the hydrological distinction was more sensitive to land use and cover changes. The calibration (NSE=0.78) and validation (NSE=0.81) model results showed satisfactory fits between measured and simulated discharge in the studied period (1995-1998 and 2008-2012). The satisfactory fits demonstrated the potential of the SHETRAN model in examining the effect of land use and cover changes on the streamflow variations assessment in the tropical regions. The increase in the model efficiency was attributed to the increase in the amount of rainfall received in the validation period. This study tallies with the findings of Indeje *et al.,* (2000) who revealed that the El Nino (ENSO) explains about 50 percent of the East African rainfall variance with other factors explaining the remaining variance.

The conversion of natural land cover to create more land for agriculture and settlement purposes caused a more profound effect on the canopy storage, subsurface, channel and land surface storage, and soil evaporation resulting into streamflow differences as per the model output. Evans (1996) also found out that the present land use and cover changes have more significant effects on the streamflow. The present increase in the streamflow could be attributed to the increase in surface flow during the rainy seasons, which is related to reduced infiltration after the conversion of land cover to other land use options (Lindenschmidt *et al.,* 1998; Marcos *et al.*, 2003) in the catchment.

The effects of land use and cover changes had more impact on the variations of streamflow than evapotranspiration and rainfall in the studied period. This is explained by the present sparse and small patches of land cover that do not siginficant influences on evapotranspiration and rainfall to a large extent (Nien-Ming *et al.*, 2009). This study is also in line with the results of many scholars who argued that the integration of land use and cover changes into hydrological models have largely resulted into increasing streamflow (Hua *et al.*, 2008; Hurkmans *et al.,* 2009; Schilling *et al.,* 2010; Nutchanart and Wisuwat, 2011).

The highest change in the gain of land was mainly experienced from the agricultural land use (crop growing) and tropical forest (regeneration); while, the highest change in the loss of land was largely experienced from wetlands, and bushlands and thickets refer to Figure 7.4 and Table 7.1. The findings of this study tally with those obtained by Place and Otsuka (2000); Otieno and Buyinza (2010) who observed that population pressure, customary tenure system, illegal human activities such as charcoal burning, wood fuel collection and farming activities are largely responsible for forest cover clearing in the region where Malaba River catchment is situated. Delve and Ramisch (2006) also found out that in Eastern Uganda on average, rural households derive nearly three-quarters of their income from crop farming and therefore smallholders dominate the agricultural sector with over 90 percent of crop production being produced on farms averaging less than 2 hectares. Walsh *et al.,* (2001) also noted that the conversion of land cover is a major driving force behind land degradation in the Malaba River Catchment thus has caused significant effects on the hydrological cycle.

The prolonged increase in the streamflow of the Malaba River in the last quarter of the year is similar to the results of other hydrological studies carried out in the region. For example, because of changes in land use and cover, the hydrology of the Mara River also changed, with sharp increases in flood peak flows by 7 percent, and an earlier occurrence of these peaks by 4 days between 1973 and 2000 (Mati *et al.,* 2008). This was attributed to severity of flood events. Generally, the coverage of woodlands, tropical forest regeneration, agriculture and built-up areas had the highest influence on the variation of hydrological components in the studied period (1995-2012). However, the agricultural land use (crop growing) had the highest influence on the components (streamflow, evapotranspiration and rainfall) than the other land use and cover types. Meanwhile, the least influential land use and cover on the hydrological components during the studied period was open water.

7.5 Conclusion

The catchment experienced a shift in the length of streamflow availability from the months of April - October in 1995 to August - December in 2012. The agricultural land use (crop growing) and tropical forest were the most determinant land uses and cover of streamflow variations in the catchment. The depletion of natural land cover to create more land for agriculture and settlement purposes caused more profound impacts on the canopy storage, subsurface flow, channel and land surface storage, and soil evaporation resulting in streamflow differences as per the model results. The study noted that the agricultural land use (crop growing) had a higher influence on the hydrological components than the other land use and cover options in the catchment.

This chapter focused on assessing the extent of land use and cover changes and their effect on the streamflow of the Malaba River catchment. This assessment is important for the management and ecological restoration of the catchment natural resources (water and land). The subsequent chapter synthesizes the results from the previous chapter 3 to 7.

Chapter 8

Synthesis of findings, conclusion and recommendations

8.1 Introduction

This chapter brings together the different strands of this study, based on the findings, conclusions and recommendations. The chapter provides a review of hydrological responses resulting from changes in land use and cover in the Malaba River catchment. The review is based on the effect of extreme weather events, land use and cover changes, sediment loading/concentration, changes in soil properties, and river channel morphology in regard to the streamflow variations in the Malaba River Catchment. This is followed by the presentation of future research direction, recommendations and conclusion.

8.2 Evaluation of the study

This study demonstrated how changes in land use and cover affected the hydrological components (streamflow, precipitation and evapotranspiration) in a tropical catchment. In particular, this study combines factors such as extreme weather events; soil-infiltration, river bank stability and sediment concentration influenced by changes in land use and cover. The direction of this research provides comprehensive information required in the modern management of water resources and other catchment related natural resources. Information on the factors affecting the hydrological components in the catchment were extracted with the use of remote sensing and geographical information systems techniques; application of the SHETRAN/IHACRES/SCS-CN hydrological modelling systems, soil and sediment sampling, soil infiltration experiments, river cross-sectional geometrical analysis, and use of drought indices. These methods have proved to be a prerequisite in assessing the effect of land use and cover changes in hydrological response related studies. The study results are reviewed below.

8.3 Review of research findings

8.3.1 Extreme weather events and streamflow

This study has demonstrated that an understanding of extreme weather events in relation to streamflow is critical in hydrological response and land use studies. The study notes that the frequency and severity of extreme weather events had reduced from 4-10 to 1-3 years over the catchment. This shows that the catchment is experiencing higher and more frequent peaks of streamflow in a shorter return-period. The rainfall pattern in the catchment has also significantly changed in the last 30 years. This is ought to greatly influence rainfall-runoff generation, streamflow, and river bank erosion. The assessment of extreme weather events coincided with the El Nino Southern Oscillation events that were recorded in Uganda. Therefore, the comparison between drought indices and a hydrological model showed that hydrological models (rainfall conceptual models) can also be used monitor droughts in the tropics.

8.3.2 Land use and cover change in the rainfall-runoff generation and volume

The study results revealed that investigating the effect of land use and cover change on the soil properties in relation to rainfall-runoff generation is a prerequisite to understanding streamflow pathways and their dynamics in a catchment (Niehoff, 2002; Pfister, 2004). This study also confirms that the prevailing catchment land use and cover types have a more significant impact on the content of nitrogen, sand, phosphorus and organic matter than on the content of clay and silt. This is as a result of continuous cultivation of land to meet the food demands of the surrounding communities. The agricultural land use (crop growing) had a higher effect on the rainfall-runoff generation than areas, which were under forest, and bushlands. However, this study also confirms that the influence of land-use conditions on storm-runoff generation depended greatly on the rainfall event characteristics and on the related spatial scale (Niehoff *et al.,* 2002). The low rates of saturated hydraulic conductivity in the agricultural land use types (crop growing) showed that their impact on the rainfall-runoff generation was moderate. The

SCS model estimated a higher runoff volume generated from agricultural land use (crop growing) (71,740 m^3), than from bushlands and thickets (42,872 m^3) followed by the forest cover catchment wide. The variations are attributed to the rates of evapotranspiration and canopy storage.

8.3.3 The extent and effect of gold mining on sediment loading and streamflow

This study revealed that human-induced sediment loading had a high impact on the concentration of suspended sediments that led to the fluctuation of streamflow than runoff from the sampled streams. The rates of sediment deposition were higher in the dry season than in the rainy season. This resulted into reduced river water-levels, streamflow course diversions and colonization of stream-banks by riparian vegetation. The study also showed that the increase in the gold mining activities in the catchment were attributed to livelihood diversification, weak environmental and mineral laws and the customary land tenure system. The coarse and medium sand, and also silt had the most significant impact on the distribution of bed deposit particle sizes that were found on the sampled river channel beds. This was because the materials found on the river channel bed were influenced by changes in the sediment supply (Jayne and Mossa, 1999) and stream bank erosion. This study also highlights that information on the weight and grain size of sediments is of increasing interest in the management of sediment transport and water related problems (Xu, 2007).

8.3.4 Land use and cover change on the river channel morphology and streamflow

This study further revealed that the highest concentration of suspended sediments was recorded from the wetland, bushlands, tree-plantation, tropical forest and agricultural landuse. Fine sand, silty sand and silty clay were the most predominant types of river bed deposit particle grain sizes that dominated the channel bottom. The tree plantation and bushland cover types had the most stable river banks compared to wetland and agricultural land use and cover types. The agricultural land use (crop growing) experienced the highest rates of both channel aggradation and degradation than the channel under tree plantation. The rates were a result of agricultural intensification and livestock trampling of the stream bank in search for drinking water under the tree plantation. The channel morphological parameters (stream depth, width, and discharge) also had a significant contribution on the concentration of suspended sediments and thus an increase or decrease in the stream water levels. The main drivers of the channel morphological change in the catchment were; floods (bank erosion), farming practices, urbanisation, livestock rearing, industrialisation, and the nature of channel morphology among others. The results of this study will help managers define policies based on a longer-term perspective, with an appreciation for the dynamic nature of river channels (Montgomery and Buffington, 1997).

8.3.5 Land use and cover changes on the streamflow

The SHETRAN hydrological model results showed that the changes in land use and cover influenced the catchment streamflow in the studied period. This study also notes that it is possible to apply the spatially distributed hydrological models in the tropics. But these should be utilised with care because of meteorological data and discharge challenges such as inadequacy, inconsistencies. The study results of peak and low flow conditions in the calibration period were mainly attributed to the agricultural and tropical forest land use and cover types. The current land use and some cover types are a result of the depletion of natural land cover to create more land for agriculture and settlement. These have caused profound effects on the canopy storage, subsurface flow, channel and land surface storage, and soil evaporation resulting into streamflow differences as per model results.

The study also noted that the highest change in the gain of land was mainly experienced from the agricultural landuse and tropical forest-regeneration, while the highest loss of land was experienced from the wetlands and bushlands and thickets. This study strongly confirms that hydrological modelling is perhaps one of the only means by which to study the individual and combined impacts of multiple factors affecting the hydrology of large and medium catchments (Qi *et al.*, 2009). This knowledge can therefore be used as the basis for catchment management in order to be able to compensate for land use and cover change effects (Elfert and Bormann, 2010).

8.4 Recommendations

This study notes that the frequency and severity of extreme weather events frequency had reduced from 4-10 to 1-3 years over the catchment. Therefore, in order for the catchment to adapt to these events, there is need to protect the boundaries of the Malaba River and its tributaries. The protection mechanisms should first maintain the buffer zone of one hundred meters (100 m) calculated from the river as set by National Environmental Management Authority in the country. Secondly, there is need to carry out afforestation and mulching programmes along the river. This study also notes that hydrological models especially the rainfall conceptual models can be used to assess the frequency and severity of extreme weather events.

The study has shown that the highest change in the gain of land was mainly experienced from the agricultural land use (crop growing) and tropical forest-regeneration. Therefore, there is an urgent need to enforce environmental laws to minimize on the encroachment of fragile ecosystems such as wetlands and forests. The decline in the areas covered by land cover is attributed to the search for fertile land for crop growing and trees for charcoal burning and firewood. There is also need to promote soil and water conservation programmes in the catchment.

This study notes that much as the spatially distributed hydrological model was ideal for this study in the modelling of streamflow response to changes in land use and cover; they should be applied with care. This is because the model is over parameterised and does not explicitly define or include the nature/type of wetlands found in the tropics.

The findings showed that human-induced sediment loading had a much higher impact on the concentration of suspended sediments and streamflow than rainfall-runoff from the sampled streams. Therefore, the study demonstrates that there is a need to sensitize the miners about the effect of washing pounded gold ore in the open water sources, which is causing a reduction in the water levels, heavy metal pollution and decolonisation of river banks by the vegetation. This study suggests that a central ore grinding and washing place should be created and utilized by all the miners to minimise on the damage.

There is also need to develop land restoration programmes such as backfilling of abandoned mined pits. The restoration programmes should increase land productivity by facilitating agricultural production, which is the main source of livelihood. This study also notes that there is need to carry out annual environmental impact assessments by the local government in a bid to have a clear understanding of the extent of mining activities and their effects on the catchment water resources.

There is also need to create a co-operative framework and develop common policies for the joint management of the water resources in the Sio-Malaba-Malakisi River Basin, which is shared between Uganda and Kenya. For instance, wetlands are owned by the government in Uganda, while in Kenya there are owned by individuals. Therefore, having common policies on their management and utilisation is important since they play an important role in the regulation of water into the Malaba catchment.

In addition, there is need to implement data quality control mechanisms for stream flow and meteorological data collected by the Ministry of Water and Environment in Uganda. This will reduce the reliance on limited and inconsistent hydro-meteorological data. The aim should be to secure scientific information, and not to rely on speculation. The prediction of extreme weather events, streamflow, and climate change should become more reliable.

This study gives a good indication on the trend of planform stability and the effects of past channel planform modification on the streamflow. Therefore, there is a need for more planform assessments to be carried out in the catchment prior to the establishment of engineering structures and water resources management plans.

8.5 Further research

The synthetic analysis of the study findings identified the following gaps for further research

- Quantification of overall catchment rainfall-runoff through field measurements
- Prediction of the future hydrological responses to changes in land use and cover in the catchment
- Evaluation of land and water degradation aspects attributable to changes in the farming systems

8.6 Conclusion

This study reveals that the catchment is currently experiencing a high frequency and severity of drought and flood events. The performance of the IHACRES model corresponded with the results obtained from the SPI and CDI drought indices especially during the severity of drought and flood events recorded in the catchment. In terms of the extent of the land use and cover changes. The highest change in the gain of land was mainly experienced from the agricultural land use (crop growing) followed by tropical forest (regeneration) and lastly from both woodland and built-up land use and cover types. The changes in land use and cover explain why there was a significant prolonged availability of streamflow in 1995 than in 2012 that occurred from April to October. However, this study also notes that there was a shift in the length of streamflow availability from the months of April - October in 1995 to August-December in 2012.

The agricultural land use (crop growing) had a relatively high rate of rainfall-runoff generation than areas, which were under tropical high forest, and bushlands. The SCS-Curve-Number model estimated a comparatively higher runoff volume generated from agricultural land use (crop growing) and bushlands and thickets than in the tropical high forest cover. The human-induced sediment loading had a much higher impact on the concentration of suspended sediments and fluctuation of discharge than the concentration of rainfall runoff from the sampled streams. The extent of gold mining land use has increased in the catchment as noted by this study.

The modification of streamside/ riparian land use and cover types was responsible for the variations of streamflow and channel geometry in the catchment. This change has been reflected in the narrowing of the channel planform between 1986 and 2013. The tree plantation and bushland cover types had the most stable river banks from the sampled land use and cover types. The study noted that the agricultural land use (crop growing) experienced higher rates of both channel aggradation and degradation than the tree plantation cover type. This study strongly affirms that the stability and instabilities facing the river channel geometry had a significant impact on the variation of the catchment streamflow from the sampled land use and cover types. Therefore, there is need to monitor and assess the catchment wide degradation of land use and cover types because they are a threat to the river channel morphology.

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