Streamflow responses to changes in land use and climate in a tropical catchment: Malaba River Catchment, Eastern Uganda

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ABSTRACT

The hydrological cycle over most tropical catchments is mainly influenced by changes in land use and climate. This study explored the trend of precipitation and streamflow to evaluate the sensitivity of the catchment to land use and climate. A Mann-Kendall test and the concept of streamflow elasticity were adopted to determine the trend of precipitation and sensitivity of the catchment to climate. Changes in land use on the streamflow were evaluated using a spatially distributed SHETRAN hydrological model. The model calibration period was 1995-1998, while 2009-2012 was the validation period. The highest change in the gain of land were mainly experienced from the agricultural land use (crop growing) (36.7%) and tropical forest-regeneration (2.2%); while the highest loss in land were 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 whilst 0.81 during validation. The high frequency of flood re-occurences and growth in agricultural land use were the major contributors of streamflow in the catchment.

Key words: Land use, climate, streamflow, SHETRAN model, Malaba River

1.0 Introduction

Changes in land use and climate 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). Streamflow responses to changes in land use and climate 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 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 changes in land use and climate can be a basis for improved water resources management and ecological restoration of most catchments (Kashaigili, 2008; Nie *et al.,* 2011).

It is important to note that the rate and extent of changes in land use and climate 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 Niña conditions in the wet 1970s (Siriwardena *et al.,* 2006; Jorge *et al.,* 2012).

The effects of changes in land use and climate on the catchment hydrology are dependent on the individual characteristics of the catchment such as topography, bare rock, and type of soil (Moran-Tejeda *et al.,* 2010). Therefore, investigating the effects of changes in land use and climate 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 changes in land use and climate 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 climate affect the water balance and hydrological cycle is still inadequate in the field of hydrological research in respect to streamflow (Overgaard *et al.,* 2005).

To address this inadequacy, there are numerous well known general hydrological models currently developed and utilized worldwide to investigate the effects of changes in land use and climate 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 changes in land use and climate on the streamflow of the Malaba River Catchment.

1.1 Materials and methods

1.1.1 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 size of this mid-sized catchment is 2,232 km^2. 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) and later drains into Lake Kyoga. About seventy percent of the river is situated in Uganda (midstream and downstream), while the remaining portion is in Kenya (upstream) (Figure 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. Petric plinthosols, and Gleysols are the major soil types found in the catchment. The other soil types are 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).

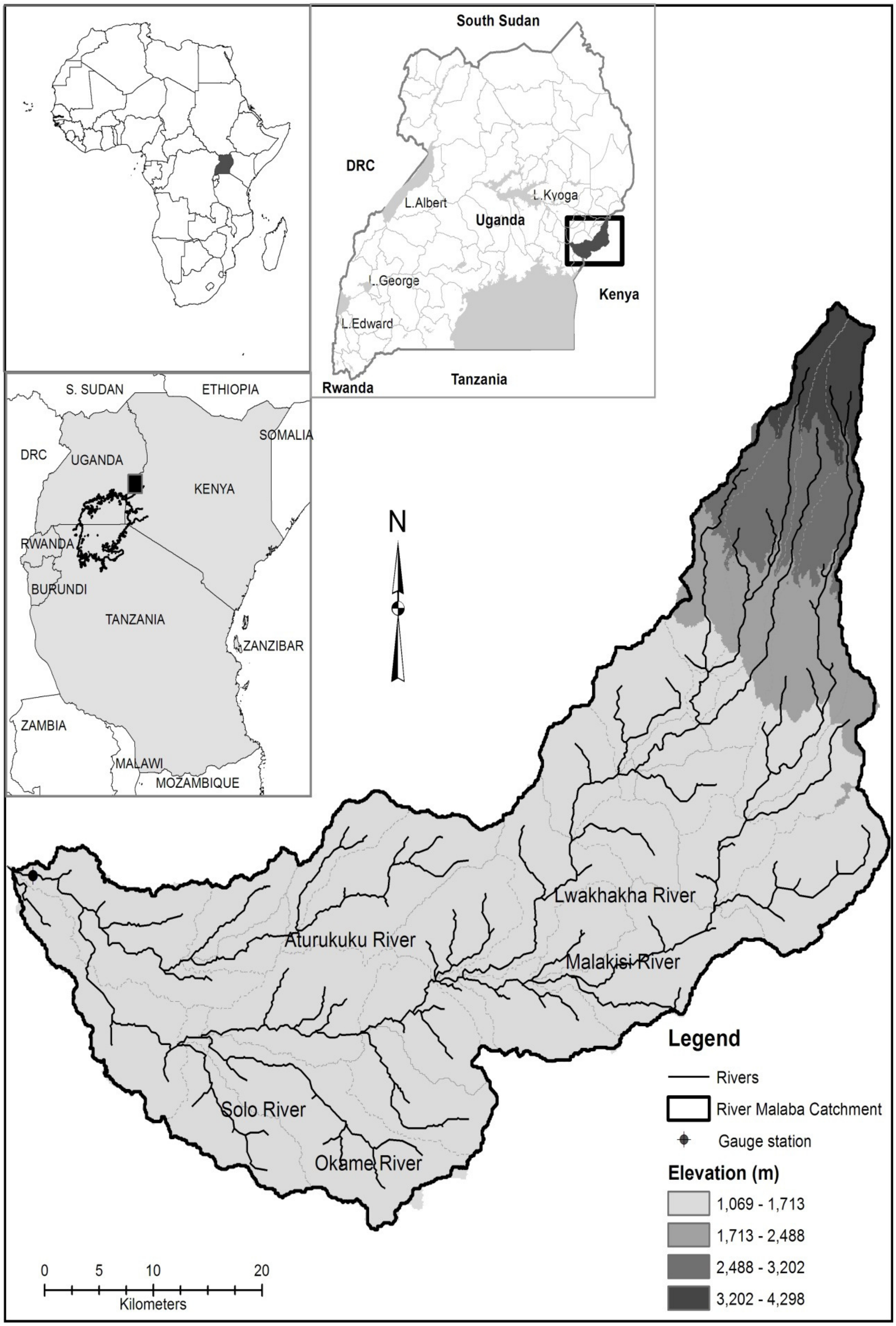

Figure 1: The Malaba River Catchment

1.1.2 Trend of Precipitation

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

The linear model *f(t)* is described as expressed by Sen (1968) as: 1

$$f(t) = Qt + B$$

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

$$Q_i = \frac{x_j - x_k}{j-k}, i = 1, 2, ...N, j > k \qquad 2$$

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:

$$\beta = \begin{cases} T_{\frac{N+1}{2}} & \text{N is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{N is even} \end{cases} \qquad 3$$

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:

$$S = \sum_{k=1}^{n-1}[\sum_{j=k+1}^{n} \text{sgn}(R_i - R_i)] \qquad 1$$

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:

μ = 0

σ = n(n – 1) (2n + 5)/18 2

The z-statistic critical test for various significance levels

Z = |S| /σ0.5 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

$$Vk = \sum_{i=1}^{k} \text{sgn}(x_i - x_{median}) \qquad k = 1,2,3,\ldots,n \qquad 4$$

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√n

α = 0.05 1.22√n

α = 0.01 1.63√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.

1.1.3 SHETRAN model and Data preparation

1.1.3.1 SHETRAN model Description

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 data 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 are 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.

1.1.3.2 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 following 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). The variation was acceptable for the data to be incorporated into the hydrological model. The daily evapotranspiration data was also disaggregated into hourly data using the System for Automated Geo-scientific Analyses (SAGA) software.

1.1.3.3 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) images 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 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 a 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 (NBS) (2003) land use and cover classification scheme for the description of land use and cover classes in Uganda. 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.

The classified images were validated using ground-truthed data. The NBS cover map of 2008 was used a reference in image classification accuracy assessment. An error matrix algorithm was adopted for image classification 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.

1.1.3.4 Topographical and soil physio-chemical 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; Antonić *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 (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 types 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).

1.1.3.5 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 (Klemeš, 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.

1.1.3.6 Nash-Sutcliffe Efficiency

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

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

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).

1.1.4 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.

1.1.5 Climate Elasticity of Streamflow

The sensitivity of the catchment to climate variability were investigated using climate elasticity of streamflow . This can be defined by the proportional change in streamflow *Q* divided by the proportional change in a climatic variable such precipitation *P.* Thus precipitation elasticity of streamflow is defined as:

$$\varepsilon p(P,Q) = \frac{dQ/Q}{dP/P} = \qquad (1)$$

The above equation was defined at the mean value of the climatic variable as:

$$\varepsilon p(\mu_p,\mu_p) = \left.\frac{dQ}{dP}\right|_{P=\mu p}\frac{\mu_P}{\mu_Q} \qquad (2)$$

Where μ_P and μ_Q are the mean values of precipitation and streamflow respectively. This expression is sensitive to a mathematical model structure and model calibration. The power law model and a linear statistical model were used to represent the relationship between annual streamflow (Q) and annual Precipitation (P). The precipitation elasticity of the power law model is given as follows

$Q = \alpha P^{\beta}$ is $\varepsilon_P^I = \hat{\alpha}\hat{\beta}(\hat{\mu}_P^{\beta} / \mu_Q)$

Where $\hat{\alpha}$ and $\hat{\beta}$ are the least square estimators of the model.

The elasticity estimator of the linear statistical $Q = \varphi +_{\gamma} P + \eta$ is $P_{Q,P}(C_Q / C_p)$ where $p_{Q,P}$ is the cross correlation of Q and P, CQ and Cp are the variation coefficients. The model parameters are φ, γ being η independent and identically distributed model errors with mean zero and variance $\sigma^2\eta$.

2.1 Results

2.1.1 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 2 and Table 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 2 and Table 1). The overall image classification accuracy assessment was 80.4%, while user's accuracy was 98.1% and producer's accuracy at 80.1%.

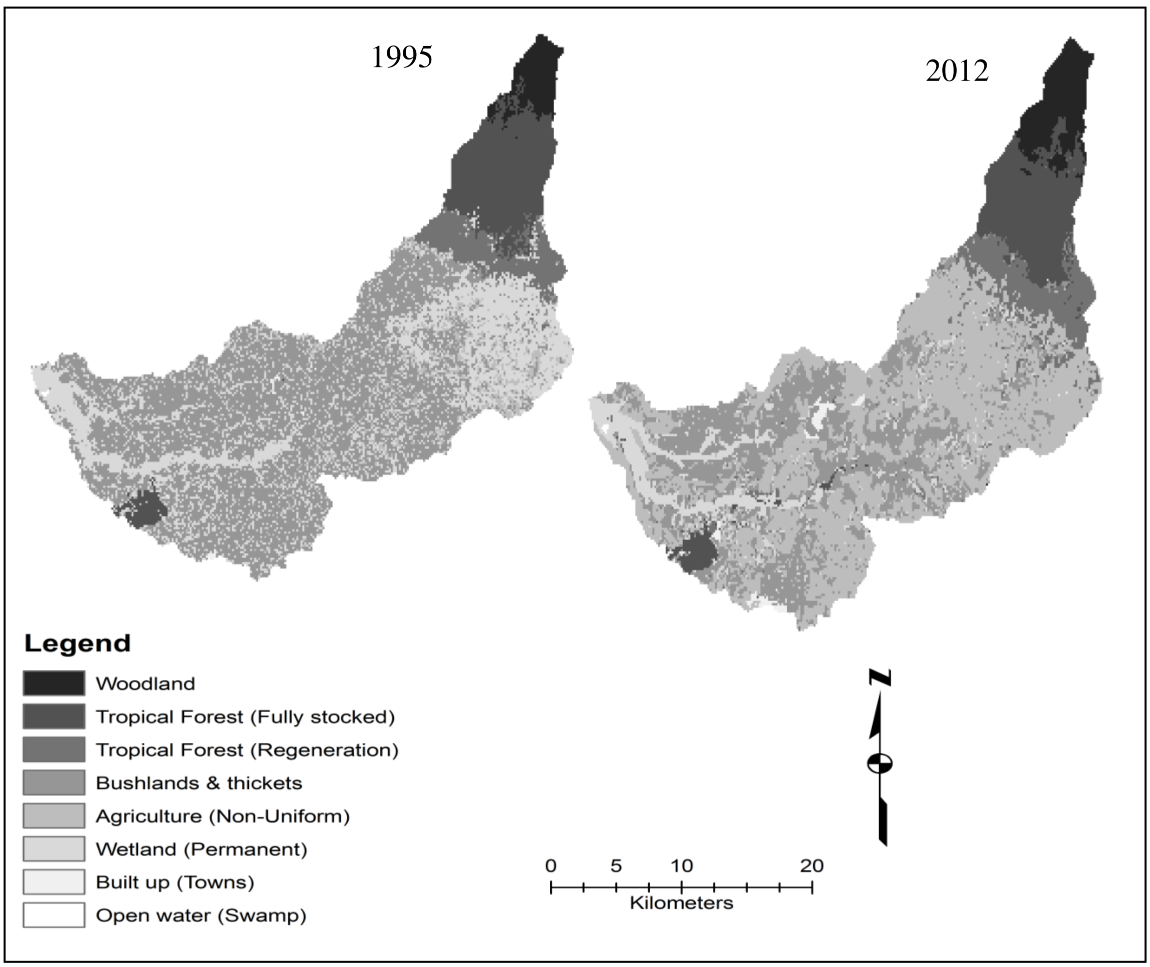

Figure 2: Land use and cover changes period 1995-2012

Table 1: Percentage of land use and cover changes in the 1995-2012 period

	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

2.1.2 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. 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. 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. 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 2). The temporal variation and intensity in the annual rainfall changes also gave an important insight on the trend of streamflow in the catchment.

Table 2: Sen's slope estimate and significance of annual rainfall trend

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)

2.1.3 Mean variation of the hydrological components

Table 3 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.

Table 3 The mean hydrological components of the Malaba River Catchment

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

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

2.1.4 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 3).

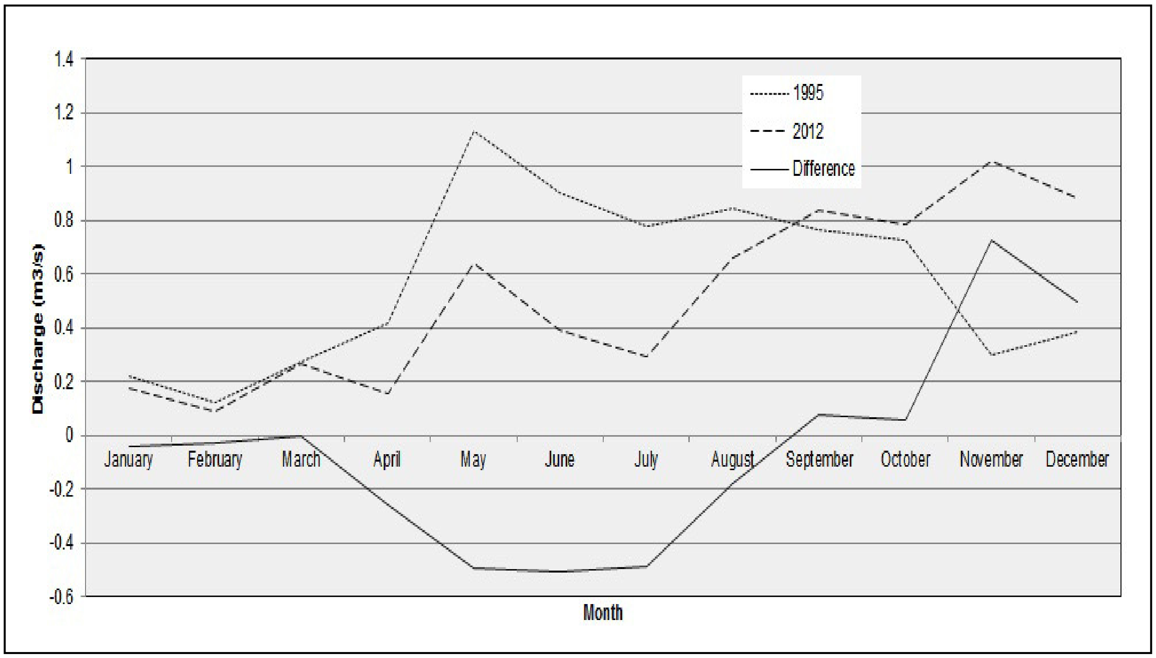

Figure 3: The availability of streamflow in the studied years (1995 and 2012)

2.1.4 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 4).

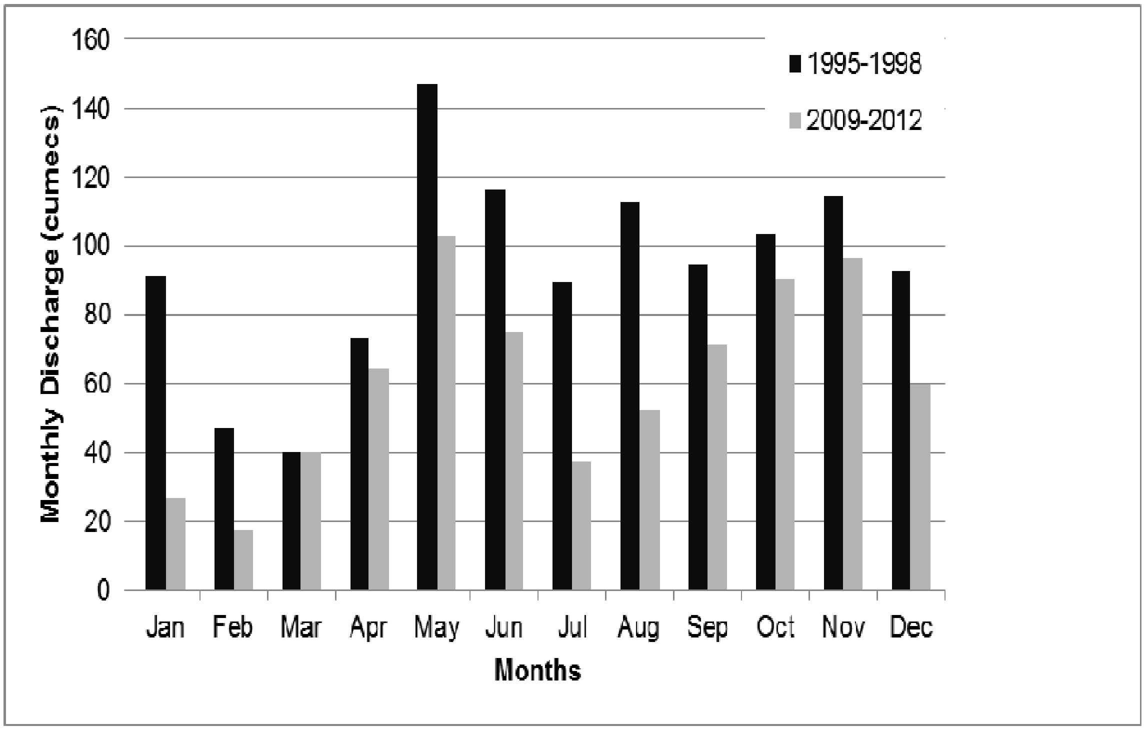

Figure 4 Seasonal distribution of streamflow between the calibration and validation periods

2.3.6 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 5) unlike in the calibration period (Figure 6). 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 $m^{1/3}s^{-1}$, while 0.06 $m^{1/3}s^{-1}$ for the validation period (Figure 6 and 5). 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.

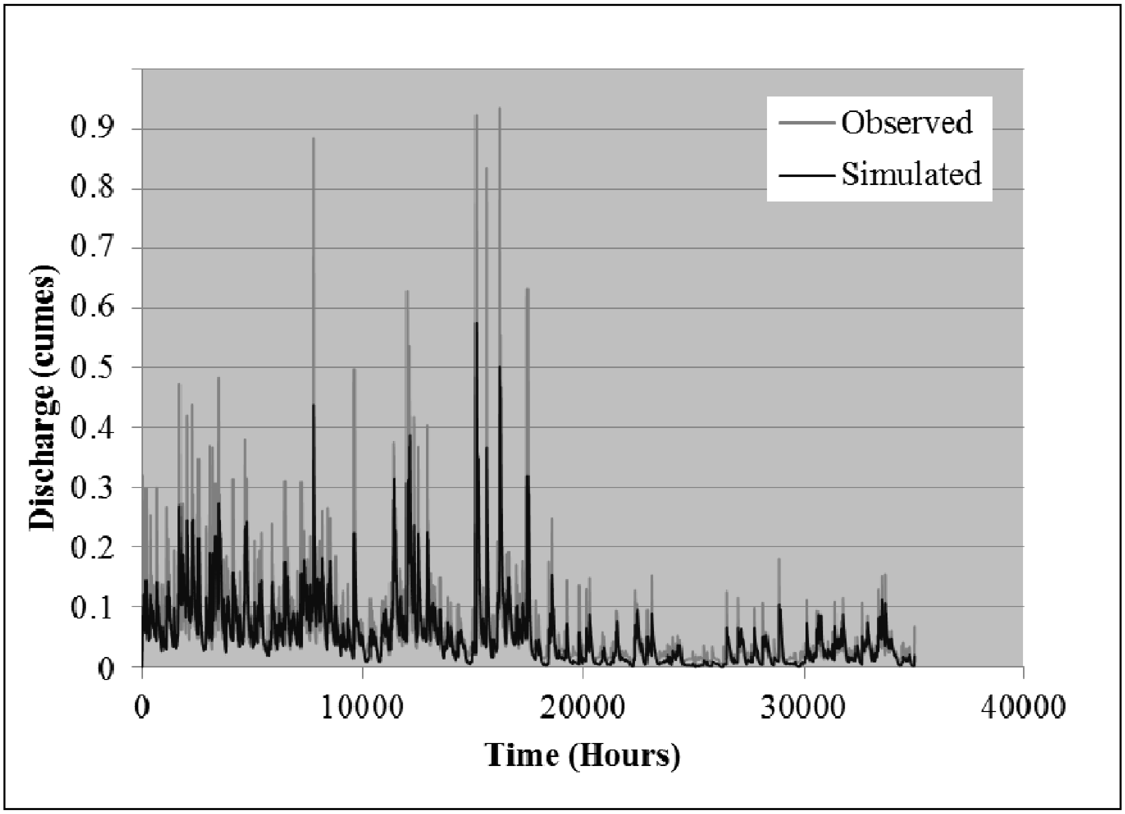

Figure 6: Calibration period 1995-1998

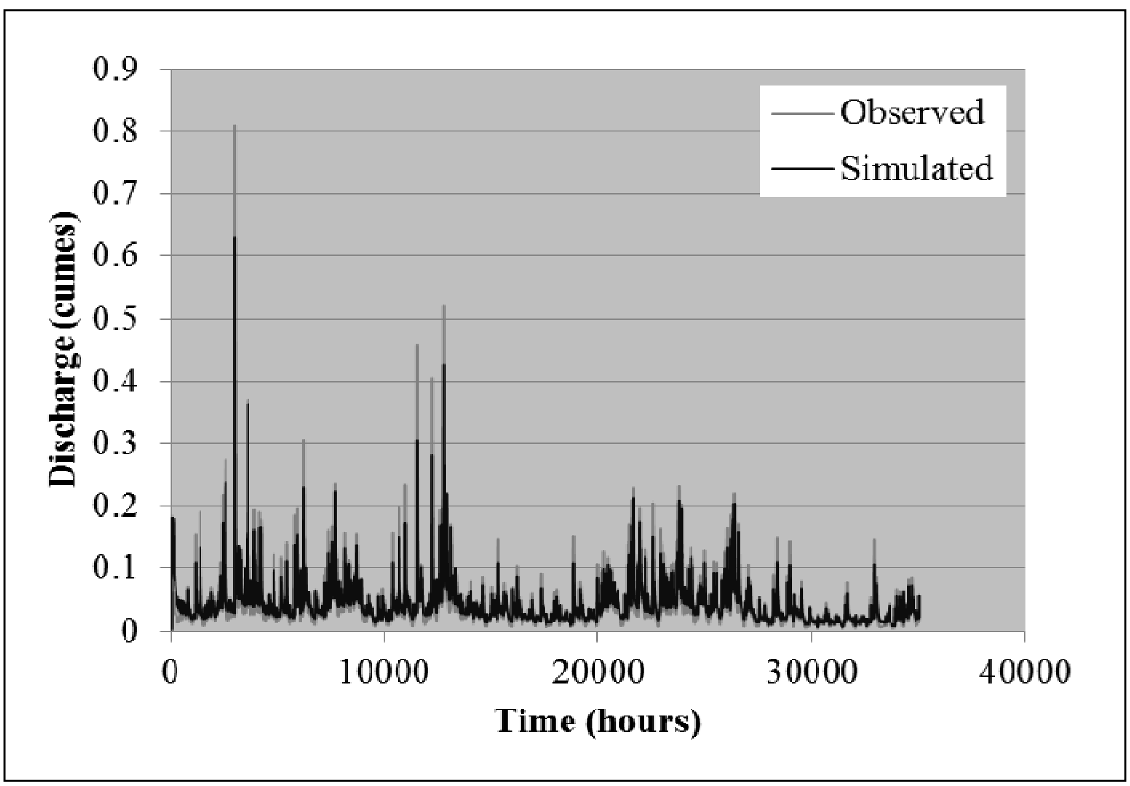

Figure 5: Validation period 2008-2012

2.3.7 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. The R-squared are listed with the direction of influence (negative or positive) in the studied period 1995-2012 (Table 4).

Table 4 Summary of multiple regression of land use and cover type (predictors) with each hydrological component response.

	Predictors								
Responses	**W**	**TFF**	**TFR**	**BT**	**AN**	**W**	**BA**	**OP**	**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); **W**= Wetland; **BA**= Built up areas; **OP**= Open water.

2.1.6 Climate Elasticity of Streamflow

Table 5: Statistics and precipitation elasticity of streamflow between 1992 to 2011

River	μ_Q (mm)	μ_P (mm)	C_Q	C_p	PQ,P	$\varepsilon^1 p$	$\varepsilon^2 p$
Malaba	196.4	1879.4	0.001	0.005	0.011	0.9438	0.9372

The results from the power law model and the linear statistical model estimated for the sub basins are closely related and this meant that the changes in precipitation were also reflected in the changes in streamflow.

3.1 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. 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 Niño–Southern Oscillation (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.. 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.

4.0 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 high frequency of flood re-occurences and growth in agricultural land use were the major contributors of streamflow 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.

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6.1 References

1. Abbott, M. B., Bathurst, J. C., Cunge, J. A., O’Connell, P. E., and Rasmussen, J. 1986a. An introduction to the European Hydrological System—Syste`me Hydrologique Europe´en, ‘SHE.’1: History and philosophy of a physically-based, distributed modelling system. *Journal of Hydrology*, **87**: 45–59.
2. Achouri, M. and Gifford, G.F. 1984. Spatial and Seasonal Variability of Field Measured Infiltration Rates on a Rangeland Site in Utah. *Journal of Range Management,* **5**:451-455.
3. Anderton, S., Latron, J. and Gallart, F. 2002. Sensitivity analysis and multi-response, multi-criteria evaluation of a physically based distributed model. *Hydrological Processes*, **16**: 333-353.
4. Antonić, O., Hatic, D. and Pernar, R. 2001. DEM-based depth in sink as an environmental estimator. *Ecological Modelling,* **138**: 247-254.

5. Bamutaze, Y., Tenywa, M.M., Majaliwa, M.J.G., Vanacker, V., Bagoora, F., Magunda, M., Obando, J. and Wasige, J.E. 2010. Infiltration characteristics of volcanic sloping soils on Mt. Elgon, Eastern Uganda. *Catena,* **80**:122-130.
6. Beven, K. J. 2001. Dalton Medal Lecture: How far can we go in distributed hydrological modelling?. *Hydrology and Earth System Sciences*, **5**: 1-12.
7. Birkinshaw, S. J., James, P. and Ewen, J. 2010. Graphical user interface for rapid set-up of SHETRAN physically-based river catchment model. *Environmental Modelling and Software,* **25**: 609-610.
8. Bowling, L.C. and Lettenmaier, D.P. 1997. Evaluation of the effects of forest roads on streamflow in Hard and Ware Creeks, *Washington, Water Resources Series*, Technical Report **155**, University of Washington, Seattle.
9. Cleve, C., Kelly, M., Kearns, F. R., and Moritz, M. 2008. Classification of the wildland–urban interface: A comparison of pixel-and object-based classifications using high-resolution aerial photography. *Computers, Environment and Urban Systems*, **324**: 317-326.
10. Debele, B., Srinivasan, R. and Yves Parlange, J. 2007. Accuracy evaluation of weather data generation and disaggregation methods at finer timescales. *Advances in Water Resources,* **30**: 1286-1300.
11. Delve, R. and Ramisch, J. 2006. Land management options in Western Kenya and Eastern Uganda. *Strategies for sustainable land management in the East African Highlands*, 319-331. Pender, J., F. Place, and S. Ehui, eds. Strategies for sustainable land management in the East African highlands. Washington, D.C.: International Food Policy Research Institute. DOI: 10.2499/0896297578
12. Dewan, A. M. and Yamaguchi, Y. 2009. Land use and land cover change in Greater Dhaka, Bangladesh: using remote sensing to promote sustainable urbanization. *Applied Geography*, **29**: 390-401.
13. Dezso, Z., Bartholy, J., Pongracz, R. and Barcza, Z. 2005. Analysis of land-use/land-cover change in the Carpathian region based on remote sensing techniques. *Physics and Chemistry of the Earth, Parts A/B/C*, **30**:109-115.
14. Elfert, S. and Bormann, H. 2010. Simulated impact of past and possible future landuse changes on the hydrological response of the Northern German lowland 'Hunte' catchment. *Journal of Hydrology,* **383**:245-255.
15. Evans, J. P. and Jakeman, A. J. 1998. Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. *Environmental Modelling and Software*, **13**: 385- 393.
16. FAO. 2002. *Guidelines for soil description*. Rome (Italy). ISBN: **92-5-105521-1.**
17. FAO. 2010. Food and Agriculture Organization of the United Nations: *Global Forest Resources Assessment Main report*, FAO Forestry Paper **163**, Food and Agriculture Organization of the United Nations, Rome, 2010.
18. Fohrer, N., Haverkamp, S., Eckhardt, K. and Frede, H. G. 2001. Hydrologic response to land use changes on the catchment scale. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere,* **26**: 577-582.
19. Foody, G. M. 2002. Status of land cover classification accuracy assessment. *Remote sensing of environment*, **80**: 185-201.

20. Hollingshead, A. B. 1996. Information suppression and status persistence in group decision making the effects of communication media. *Human Communication Research*, **23**:193-219.
21. Hua, G., Qi, H. and Tong, J. 2008. Annual and seasonal streamflow responses to climate and land cover changes in the Poyang Lake basin, China. *Journal of Hydrology.* **355**: 106-122.
22. Hurkmans, R. T. W. L., Terink, W., Uijlenhoet, R., Moors, E. J., Troch, P. A. and Verburg, P. H. 2009. Effects of land use changes on streamflow generation in the Rhine basin, *Water Resources Research*, **45**, W06405, DOI: 10.1029/2008WR007574.
23. ILM. 2004. *Support to the Management of Sudd Blockage on Lake Kyoga.* Produced for the Integrated Lake Management Project by Environmental Impact Assessment Centre of Finland, EIA Ltd.
24. Indeje, M., Semazzi, F. H. and Ogallo, L. J. 2000. ENSO signals in East African rainfall seasons. *International Journal of Climatology*, **20**: 19-46.
25. Isik, S., Kalin, L., Schoonover, J. E., Srivastava, P. and Graeme Lockaby, B. 2012. Modelling effects of changing land use/cover on daily streamflow: An Artificial Neural Network and curve number based hybrid approach. *Journal of Hydrology*. **485**:103-112.
26. Jenson, S. K. 1991. Applications of hydrologic information automatically extracted from digital elevation models. Hydrological Processes, **5:** 31–44.
27. Johnson, T. C. and Odada, E. O. 1996. *The Limnology, climatology and paleoclimatology of the East African Lakes*. CRC Press.
28. Jorge, L.P., Albert, I.J.M.V.D., Juan, P.G., Mulligan, M., Bruijnzeel, L.A. and McVicar, T.R. 2012. Detecting changes in streamflow catchments in the seasonal after partial woodland clearing in two large tropics. *Journal of Hydrology.* **60**: 416-417.
29. Jose, D. S., Jorge, A.R., Paolo, B. and Roger, A.P. 2003. Stochastic simulation of precipitation and streamflow processes. Handbook of weather, climate and water: Atmospheric chemistry, hydrology and societal impacts. ISBN 0-471-21489-2.
30. Kagawa, F. 2009. Learning in Emergencies. *Education and Climate Change: Living and Learning in Interesting Times*, 106.
31. Karpouzos, D.K., Kavalieratou, S., and Babajimopoulos, C. 2010. Trend analysis of precipitation data in Pieria Region (Greece). *European Water* .**30**: 31-40.
32. Kashaigili, J. J. 2008. Impacts of land-use and land-cover changes on flow regimes of the Usangu wetland and the Great Ruaha River, Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C*, **33**: 640-647.
33. Kenny, F., Matthews, B. and Todd, K. 2008. Routing overland flow through sinks and flats in interpolated raster terrain surfaces. *Computers and Geosciences*, **34**:1417-1430.
34. Kizito, F. and Ngirane-Katashaya, G. 2006. An Integrated basin wide planning approach for Malaba River Catchment. *In 32 nd WEDC International Conference, Colombo, Srilanka*.
35. Klemeš, V., 1986. Operational testing of hydrological simulation models. *Hydrological Sciences Journal*, **31**: 13-24.
36. Koutsoyiannis, D. and Manetas, A. 1996. Simple disaggregation by accurate adjusting procedures. *Water Resources Research*, **32**: 2105-2117.

37. Koutsoyiannis, D. and Onof, C. 2001. Rainfall disaggregation using adjusting procedures on a Poisson cluster model. *Journal of Hydrology*, **246**:109-122.
38. Lakimo. 2004. Lake Kyoga Management Plan, 2004 – 2007, *LAKIMO/LKMP/2004. LAKIMO*, Uganda
39. Li, K. Y., Coe, M. T., Ramankutty, N. and Jong, R. D. 2007. Modeling the hydrological impact of land-use change in West Africa. *Journal of Hydrology*, **337**: 258-268.
40. Lindenschmidt, K. E., Suhr, M., Magumba, M. K., Hecky, R. E. and Bugenyi, F. W. B. 1998. Loading of solute and suspended solids from rural catchment areas flowing into Lake Victoria in Uganda. *Water research,* **32**: 2776-2786.
41. Mango, L. M., Melesse, A. M., McClain, M. E., Gann, D. and Setegn, S. G. 2011. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modelling study to support better resource management. *Hydrology and Earth System Sciences*, **15**: 2245-2258.
42. Marcos, H.C., Aurelie, B. and Cardille, J.A. 2003. Effects of large scale changes in land cover on the discharge of the Tocantins River, South-eastern Amazonia. *Journal of Hydrology*. **283**: 206-217.
43. Marcos, H.C., Aurelie, B. and Cardille, J.A. 2003. Effects of large scale changes in land cover on the discharge of the Tocantins River, South-eastern Amazonia. *Journal of Hydrology*. **283**: 206-217.
44. Mati, B. M., Mutie, S., Gadain, H., Home, P. and Mtalo, F. 2008. Impacts of land□use/cover changes on the hydrology of the transboundary Mara River, Kenya/Tanzania. Lakes & Reservoirs: Research & Management, 13: 169-177.
45. McCuen, R. H. 2002. *Modeling hydrologic change: statistical methods*. CRC press. Pages 261-263.
46. McDonnell, M. J. 1981. Box-filtering techniques. *Computer Graphics and Image Processing*, **171**: 65-70.
47. Moran-Tejeda, E., Ceballos-Barbancho, A. and Llorente-Pinto, J.M. 2010. Hydrological response of Mediterranean headwaters to climate oscillations and land cover changes: The mountains of Duero River Basin (Central Spain). *Global and Planetary Change.* **72:** 39-49.
48. Murray, C.L., 2009. Hydrology: catchment vegetation and runoff. *Progress in Physical Geography*. **33**: 837-844.
49. Mutai, C. C. and Ward, M. N. 2000. East African rainfall and the tropical circulation/convection on intraseasonal to interannual timescales. *Journal of Climate*, **13**: 3915-3939.
50. Nash, J. and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models part 1– A discussion of principles. *Journal of Hydrology,* **10**: 282-290.
51. NEMA. 2008. *Pilot Integrated Environment Assessment of the Lake Kyoga Catchment Area.* National Environment Management Authority (NEMA), Kampala.
52. Nie, W., Yuan, Y., Kepner, W., Nash, M. S., Jackson, M. and Erickson, C. 2011. Assessing impacts of Landuse and Landcover changes on hydrology for the upper San Pedro watershed. *Journal of Hydrology*, **407**: 105-114.
53. Niehoff, D., Fritsch, U. and Bronstert, A. 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology*, **267**: 80-93.

54. Nien-Ming, H., Hone-jay, C., Yu-Pin, L., and Dung-Po, D., 2009. Effects of land cover changes induced by large physical disturbances on hydrological responses in Central Taiwan. *Environmental Monitoring Assessment*, DOI 10.1007/s10661-009-1019-1
55. Nutchanart, S. and Wisuwat, T. 2011. Effects of land cover on runoff coefficient. *Journal of hydrology*. **410**: 226 – 238.
56. Nutchanart, S. and Wisuwat, T. 2011. Effects of land cover on runoff coefficient. *Journal of hydrology*. **410**: 226 – 238.
57. Okalebo, J.R., Gathua, K.W. and Woomer, P.L. 2002. Laboratory methods of soil and plant analysis: *A working manual, Sacred African Publishers,* Nairobi, Kenya, 2nd edition, 2002.
58. Otieno, A. C. and Buyinza, M. 2010. Collaborative forest management in Uganda: A strategy for controlling deforestation in West Bugwe Forest Reserve, Busia District. *Research Journal of Applied Sciences*, **5**: 337-344.
59. Overgaard, J., Rosbjerg, D. and Butts, M. B. 2005. Land-surface modelling in hydrological perspective. *Biogeosciences Discussions,* **2:** 1815-1848.
60. Partal, T and Kahya, E. 2006. Trend analysis in Turkish precipitation data. *Hydrological processes*, **20**:2011-2026. doi:10.1002/hyp.5993.
61. Place, F. and Otsuka, K. 2000. Population pressure, land tenure, and tree resource management in Uganda. *Land economics*, **76**: 233-251.
62. Planchon, O. and Darboux, F. 2002. A fast, simple and versatile algorithm to fill the depressions of digital elevation models. *Catena,* **46**: 159-176.
63. Qi, S., Sun, G., Wang, Y., McNulty, S.G., and Moore Myers, J.A. 2009. Streamflow response to climate and landuse changes in a Coastal Watershed in North Carolina. *American Society of Agricultural and Biological Engineers.* **52**: 739-749.
64. Rawls, W. J. and Brakensiek, D. L. 1989. Estimation of soil water retention and hydraulic properties. *In Unsaturated flow in hydrologic modelling* (pp. 275-300). Springer Netherlands.
65. Roberts, G. and Crane, S. B. 1999. The effects of clear-felling established forestry on stream-flow losses from the Hore sub-catchment. *Hydrology and Earth System Sciences*, **1**: 477-482.

66. Sankarasubramanian, A., Vogel, R. M., & Limbrunner, J. F. (2001). Climate elasticity of streamflow in the United States. *Water Resources Research*, *37*(6), 1771-1781.

67. Schilling, K.E., Kung-Sik, C., Hai, L. and You-Kuan, Z. 2010. Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississippi River. *Journal of Hydrology.* **387**: 343-345.

68. Sen, P. K. 1968: Estimates of the regression coefficient based on Kendalls tau. *Journal of the American Statistical Association*, **63**:1379–1389.
69. Shalaby, A. and Tateishi, R. 2007. Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. *Applied Geography*, **27**: 28-41.

70. Siriwardena, L., Finlayson, B. L. and McMahon, T. A. 2006. The impact of land use change on catchment hydrology in large catchments: The Comet River, Central Queensland, Australia. *Journal of Hydrology*, **326**: 199-214.
71. Sloan W.T. 2000. A physics-based function for modelling transient groundwater discharge at the watershed scale. *Water Resources Research*, **36**: 225-241.
72. Sullivan, A., Ternan, J. L. and Williams, A. G. 2004. Land use change and hydrological response in the Camel catchment, Cornwall. *Applied Geography*, **24**: 119-137.
73. Tarboton, D. G. 2003. Rainfall-runoff processes. Utah State University.
74. Vijay, P.S. and Woolhiser, D.A. 2002. Mathematical modeling of watershed hydrology. *Journal of Hydrologic Engineering*. **7:** 270-292.
75. Walsh, C. L. and Kilsby, C. G. 2007. Implications of climate change on flow regime affecting Atlantic salmon. *Hydrology and Earth System Sciences Discussions*, **11**: 1127-1143.
76. Woonsup, C. and Brian, M.D. 2008. Assessing hydrological impact of potential land use change through hydrological and land use change modeling for the Kishwaukee River Basin (USA). *Journal of Environmental Management.* **88**: 1119-1130.
77. Zhi, L., Wen-zhao, L., Xun-chang, Zhang, and Fen-li, Z. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology,* **377**: 35-42.