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Assessing the Effects of Deforestation on Surface Water Yields Using a Modelling Approach: The Case of Sondu River Basin

Stephen Rwigi[1,a*], Alfred Opere[1], John Muthama[1]

[1]Department of Earth and Climate Sciences, University of Nairobi, Kenya

[a]rwigik@uonbi.ac.ke

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ABSTRACT

Climatic factors determine the amount and distribution of atmospheric water received at the land surface while the land cover conditions determine partitioning of this water into different hydrological components and ultimately the catchment surface water yields. This study assessed the effects of deforestation of a tropical catchment on surface water yields with a view to addressing fluctuating flows of the rivers emanating from Mau Forest, the largest water tower in Kenya. Sondu basin traverses South West Mau Forest covering an area of 3500 km^2. The main channel in the basin flows in a south west direction into Lake Victoria in an altitudinal range of 2900 to 1130 m above sea level over a length of 173 km. Different deforestation scenarios over the basin were integrated with climate data to form inputs to a hydrologic model, Soil and Water Assessment Tool. Using model outputs, effects of deforestation on annual and seasonal surface water yields, represented by changes in streamflow volumes under different deforestation scenarios, were evaluated. Deforestation scenarios were derived from a supervised classification scheme of time series of Satellite images to show deforestation trends. Effects of deforestation on the catchment water yielding capacity were estimated as the ratio of the difference between simulated yields under different deforestation scenarios and those simulated under the pre-deforestation scenario of 1973. Results show that forest cover declined by 18.2% and a corresponding growth in land under agriculture by 18.2% in the period between 1973 and 2010. The decline in forest coverage resulted in an increase in the annual surface water yields of about 23% over the period of study. This is possibly as a result of limited groundwater recharge due to reduced infiltration capacity leading enhanced flow fluctuations and subsequently to lower flows during the dry seasons and a higher frequency of flood incidents during the wet seasons. The study has therefore, demonstrated that deforestation has reduced the stability of Mau Forest as a water tower as evidenced by fluctuations in streamflow. Conservation of the forest will enhance the catchment's water holding capacity thereby ensuring a stable water supply to rivers emanating from it as a way of combating floods and low flows in the basin.

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1. Introduction

Water is a necessary factor for sustenance of natural ecosystems that support our existence, and also a critical factor of economic productivity (1–7). Freshwater has become increasingly scarce as a result of a growing demand for domestic, agricultural and industrial use coupled with unsustainable use and pollution from anthropogenic activities and land use and land cover (LULC) changes (8–10). Land use, described as the human exploitation and utilisation of land resources (11), is an essential part of the terrestrial component of the hydrologic cycle. Changes in land use tend to alter land surface cover which has a significant influence on the catchment hydrology (12).

Pressure on land resources for purposes of providing food, water and shelter to the ever-growing human population has brought about notable changes in LULC with corresponding impacts on hydrological regimes of watershed areas (13–19). Among the most notable LULC changes that impact on a catchment’s surface water yield is deforestation; the permanent alteration of a forest to another on-forest use such as agriculture or urban development (20–24). It is well documented that deforestation primarily reduces base flow from rivers (25,26). In regions where there is limited water availability, such changes are likely to add to the scarcity of water supply particularly during the dry seasons. Understanding the impacts of deforestation on the hydrological process in a catchment area is therefore an essential task for water resources planning for the growing human populations that threaten to stretch this scarce resource to its limit (7,26,27).

Research has demonstrated that as the forest area shrinks and developed land expands, base flow in streams and rivers tends to reduce as a result of reduced recharge of groundwater reservoirs (28–32). There is therefore a need to assess changes in the level of deforestation in a watershed in order to determine how they impact on its surface water yielding capacity which is inversely proportional to the base flow yields (32). Globally, deforestation assessment has been done using multispectral satellite images (33,34). Time series of satellite images are used to derive changes in LULC that include the level of forest cover in a watershed. A series of multispectral LULC classifications are analysed to determine the inter-annual or inter-decadal changes (18,35).

Several studies on the impacts of deforestation on water resources have been carried out in Kenya. Baker and Miller (2013) found that deforestation within the upper Njoro River catchment brought about increased surface runoff and decreased groundwater recharge. (37) reported that deforestation within the Nyando River catchment resulted in increased surface runoff volumes. (14) reported an increase in surface runoff from about 55% to 68% as agricultural land cover over Nzoia basin increased from about 40% to about 64% and forest cover decreased from about 12% to about 7% between 1973 and 2001. Mungaia (2004) established that alteration of pastureland and natural forest cover into small scale farming fields in the upper catchment of Ewaso Ng’iro River resulted in decreased infiltration leading to increased surface runoffs and flash floods.

The Mau Forest Complex (MFC), one of the few remaining natural forests in East Africa, is a contiguous indigenous forest comprising the largest water tower in Kenya (5,16,39,40) and makes up the upper catchments of the main rivers draining into Lake Victoria from Kenya (41,42). The forest is also home to a rich diversity of natural resources that include, *inter alia*, forest products, micro-climate regulation and water supply (42). Notwithstanding its regional significance as critical a water resource, the forest has experienced widespread deforestation and degradation over the past few decades (42,43). Just like other high water potential areas in Kenya, the MFC is threatened by the growing human population where agriculture and settlements are continually taking high priority (39). This has resulted in large tracts of the forest, previously conserved as protected areas, being excised for settlement and agriculture since late 1940s (16,43,44). Excision and the extensive encroachment of the forest land have resulted in the destruction of over 25% of the forest since year 2000 (42).

This study attempted to investigate effects of catchment deforestation on surface water yields in an area that is experiencing rapid socio-economic development coupled with high human population growth. Specifically, the study attempted to evaluate how deforestation affects surface water yields by quantifying its contribution to changes in streamflow volumes of River Sondu between 1970s and 2010s using SWAT hydrologic model.

2. Materials and Methods

2.1 Area of study

This study was conducted in Sondu River basin on the western side of Kenya between latitudes 00º23'S and 01º10'S and longitudes 34º46'E and 35º45'E and covering an area of about 3500 km^2 and with a total of seventeen subbasins (Figure 1). Sub basins 11 and 12, which traverse the South West Mau Forest reserve with their outlet at Kiptiget river gauging station (RGS), are the focus of this study. River Sondu emanates from Sondu-Miriu Wetlands (45) and is fed by several tributaries, whose source area is the South West Mau block. The longest channel of the river traverses about 173 km from the source areas to Lake Victoria. Sondu river drops about 1800 m between the source areas at about 2900 m and the lake level at about 1130 m above sea level (42,46).

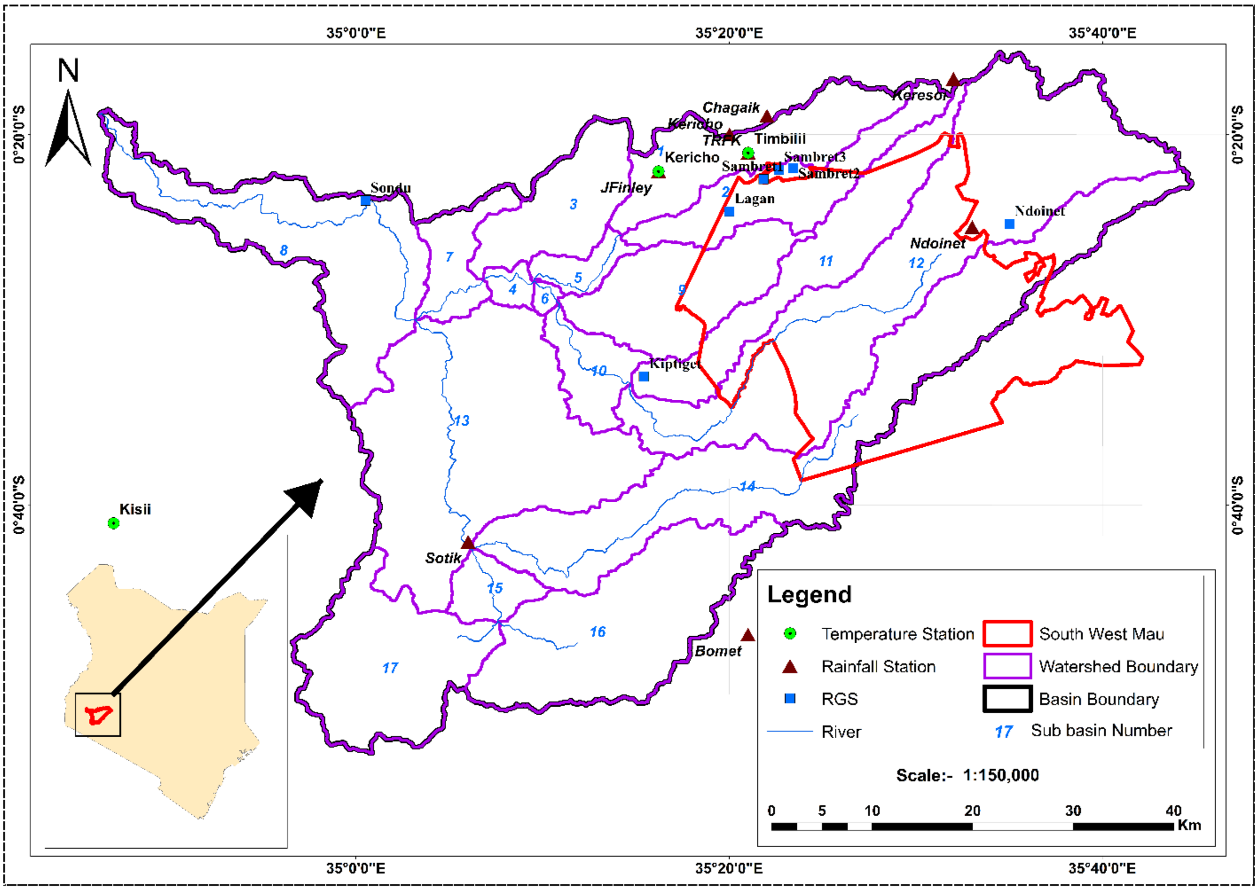

Figure 1: Sondu River basin map showing the gauging stations network and the constituent sub basins; numbers 1 to 17.

The general land uses in the basin are agriculture, forest, rain fed shrub crop (tea estates) mainly on the upper elevations bordering the forest; and settlements scattered across the basin (5,47,48). The area under forest comprises the forest reserve and covers about 84000 ha, which is about 20% of the total Mau Forest coverage. Thick Afromontane vegetation typifies the forest reserve (39,42), which plays a critical role in water flow regulation, and comprises of tall, evergreen-species that fizzle out to usher in dense bamboo bushes upstream. The areas around the forest experience annual rainfall that ranges between 1500 and 2100 mm. The forest is a source of perennial streams that feed into the main River Sondu, the main source of water to the surrounding tea estates as well as the shores of Lake Victoria South Catchment Area (42,44).

Since the study focussed on quantifying how deforestation effects surface water yields, Kiptiget sub basin (number 11 and 12 in Figure 1), was selected as the study unit. South West Mau Forest covers the entire upper catchment of Kiptiget River which constitutes a critical tributary of the main Sondu River. Any changes in the forest coverage therefore would be reflected in its flow volumes.

2.2 Assessment of Deforestation

Sondu river basin is home to large expanse of tea plantations that attract plantation workers from this region and beyond. This has resulted in the basin experiencing rapid socio-economic development that has resulted in unprecedented LULC changes over the last five decades (42). This has seen the SWM forest lose a significant part of its natural cover since 1970s (44). In order to quantify the level of deforestation of SWM forest as a result of this development, six historical multispectral satellite images of the basin taken by sensors aboard LANDSAT MSS (1973), LANDSAT TM (1986), LANDSAT TM (1995), LANDSAT ETM (2000), LANDSAT ETM+ (2010), and LANDSAT ETM+ (2018) were used. For purposes of this study, the satellite images were used to represent the basin's LULC conditions of the 1970s, 1980s, 1990s, 2000s, 2010s and 2020s respectively.

The satellite images were obtained from the Department of Resource Survey and Remote Sensing (DRSRS) in false colour composite, and were interpreted using a supervised classification scheme (7,46,49,50), guided by the AFRICOVER vegetation classification system (51), to show areas of deforestation in the catchment. Image classification of the false colour composite images of LANDSAT was used to obtain LULC thematic maps (52,53). Temporal changes in LULC between the 1970s and 2000s decades were compared over a 10-year interval and trends in deforestation were evaluated by comparing percentage changes in forest coverage at different times with the baseline forest cover of the 1970s decade. Specifically, the trend of deforestation was analysed for the number of hectares of forest that was converted to non-forest lands.

2.3 Hydrological Modelling

Soil and Water Assessment Tool (SWAT) hydrologic model ((54), is a conceptual physically-based model operating on a daily time-step to simulate the hydrology of a watershed designed for predicting impacts of catchment management practices, such as LULC change, on water quantity and quality. The model was chosen to simulate streamflow under different forest cover scenarios on account of its suitability of simulation of runoff generation and its ability to integrate different types of spatial data. Model inputs included: Digital Elevation Model (DEM), LULC, soil type and climate data from the basin (15,55).

The global Shuttle Radar Topography Mission (SRTM) 90 m DEM was applied in the delineation of the watershed into sub basins and stream network. The 1973, 1986, 2000, and 2010 LULC, cover maps derived from satellite images were reclassified into four SWAT model format categories comprising agriculture, rainfed shrub crop, open and closed forests. The spatial soil data were geo-processed to a format compatible with ArcSWAT (swat.tamu.edu/software/arcswat/) and then appended to the user soil data set (32,56).

The Model simulated the terrestrial phase of the hydrologic cycle using the water balance concept (Equation 1).

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \qquad (1)$$

Where SW_t represents the soil water content at time *t*, SW_o represents the soil water content on day *i*, t represents time in days, R_{day} represents amount of rainfall on day *i*, Q_{surf} represents the amount of runoff on day *i*, E_a represents the amount of evapotranspiration on day *i*, W_{seep} represents the amount of water entering the vadoze zone on day *i*, and Q_{gw} represents the amount of groundwater flow on day *i* (57).

2.4 Effects of Deforestation on Surface Water Yields

Analyses of effects of deforestation on surface water yields were carried out by performing four model runs (58) driven by simulated weather data from the Providing Regional Climate for Impact Studies (PRECIS) model for the period 1971 to 2010 and LULC scenarios of 1970s, 1980s, 1990s, and 2000s decades respectively. For purposes of this this study, the four LULC scenarios for the four decades were coded as were coded as LU1970s, LU1980s, LU1990s, and LU2000s respectively.

The four model runs were driven by the same time series of weather (daily) and climate (mean monthly) data between 1971 and 2010. From one model run to the next, the only model parameters that were varied were those that were defined by the different LULC scenario maps of the watershed; LU1970s, LU1980s, LU1990s, and LU2000s. Therefore, any changes in the simulated surface water yields from one run to the other were ascribed to variations in the level of forest coverage of the watershed. The effects of deforestation on the catchment surface water yielding capacity were therefore estimated using the ratio of the difference between the simulated streamflow under the LU1980s, LU1990s, and LU2000s forest coverage scenarios to the streamflow under the LU1970s baseline scenario.

3. Results and Discussions

3.1 Changes in LULC

A total of three main LULC categories were delineated in the upper parts of the basin that mainly comprises the SWM forest; forest land, grassland and cropland (Figures 2 and 3). Figure 2 shows temporal while Figure 3 shows spatial temporal changes in the different categories of LULC between 1970s and the 2020s decades. It was noted from Figure 2 that as of the baseline decade (1970s), the areal extent of these LULC categories were; forest (86.7%), grassland (9.7%), and cropland (3.5%). This coverage has since changed with time where forest coverage declined to an all-time low of 58.9% in the 2010s before rising to settle at 65.7% in the 2020s decade. Grassland, on the other hand rose to an all-time high of 25.9% in the 2000s decade before declining to settle at an all-time low of 5.1% in the 2020s decade while cropland has consistently risen from an all-time low in 1970s to an all-time high of 29.2% in the 2020s. Generally, the area under forest has been on a decreasing trend while that under cropland is on an increasing trend; a clear case of deforestation in the area.

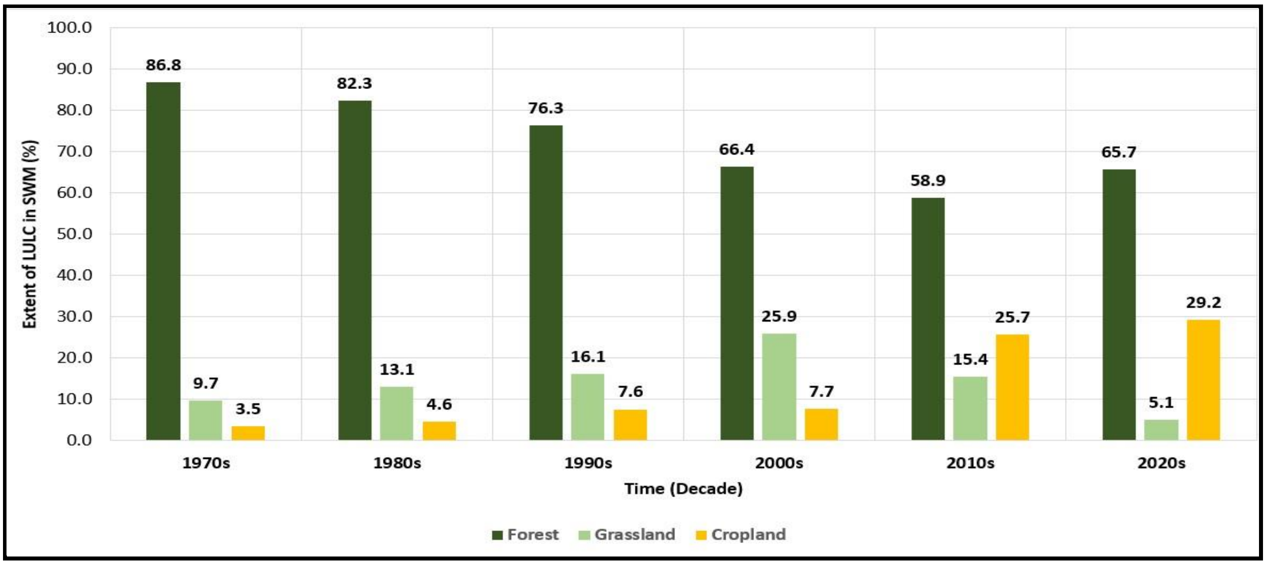

Figure 2: Temporal evolution of the three dominant LULC categories in the South West Mau Forest over a period of four decades; 1970s, 1980s, 1990s, 2000s and 2010s.

Figure 3 shows that these changes in the LULC categories are mainly concentrated in the north-eastern upper parts of the basin. This is a clear indication that SWM forest reserve has undergone some extent of deforestation where forest land has been converted to grassland and cropland. This has the potential to affect the catchment hydrology leading to fluctuations in surface water yields and rain water storage in the basin and hence to the frequent flooding incidences in the basin witnessed in the last decades.

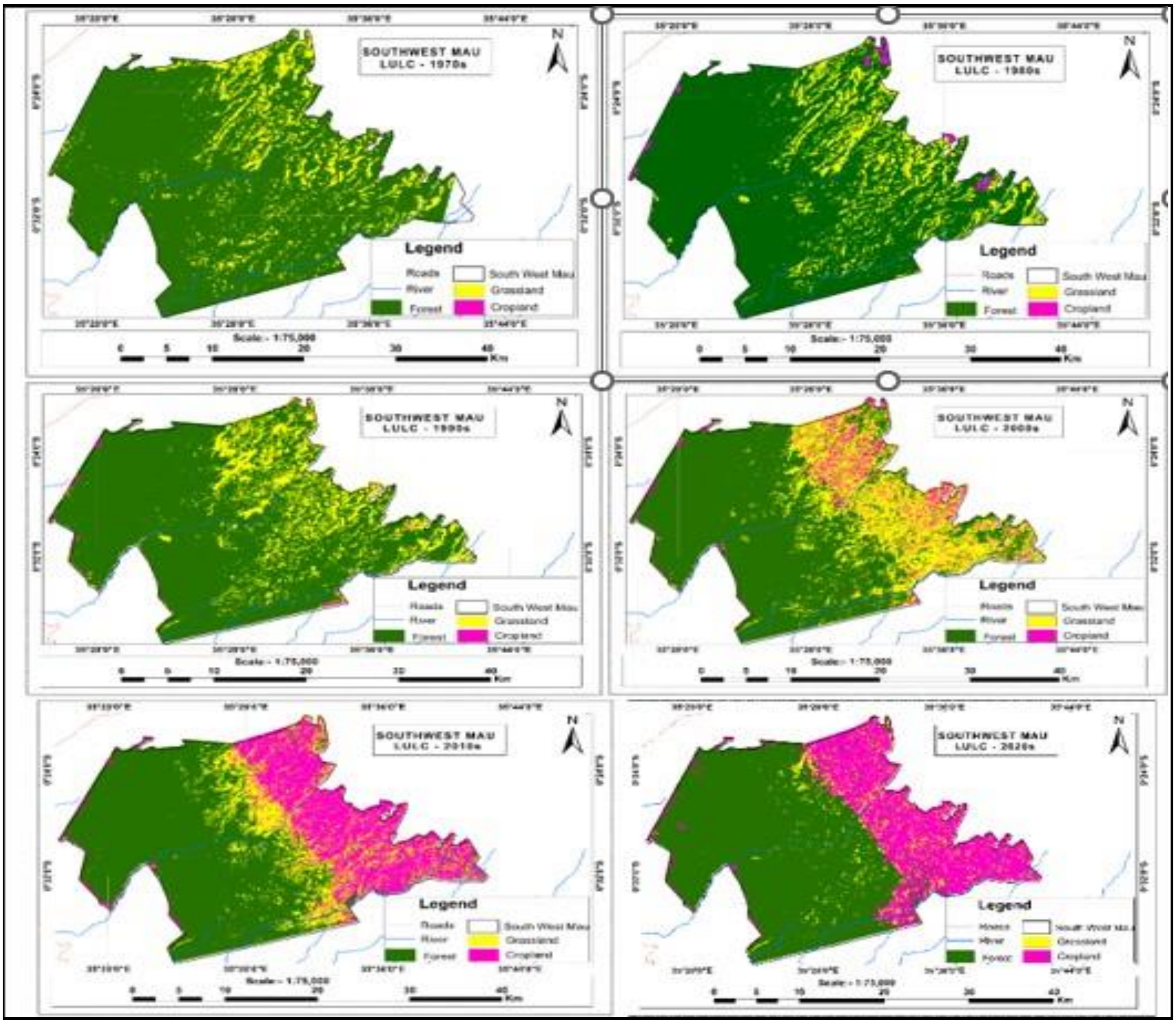

Figure 3: Spatiotemporal evolution of the three dominant LULC in the South West Mau Forest over a period of four decades; 1970s, 1980s, 1990s and 2000s.

Encroachment and degazettement of forest reserves for purposes settling a growing population are the main forces behind the deforestation of the SWM forest reserve (59). The decrease in forest coverage and the corresponding increase in land under agriculture is clear evidence that there has indeed been some deforestation in this watershed where previously land under forest coverage has been cultivated. This deforestation is likely to negatively influence the hydrology of the area through reduced infiltration, and subsequent subsurface storage, thus leading to enhanced fluctuations in surface runoff and increased incidences of flooding as has been experienced lately.

Table 1 column 2 shows the 1970s baseline LULC status within south west Mau Forest reserve while columns 3, 5, 7, 9, and 11 show the status in the 1980s, 1990s, 2000s, 2010s, and 2020s decades respectively. Columns 4, 6, 8, 10, and 12 show the percentage changes in LULC coverage with respect to the baseline (1970s decade) coverage during the 1980s, 1990s, 2000s, 2010s, and 2020s decades respectively. Positive values in columns 4, 6, 8, 10, and 12 signify increase while negative values signify decrease in the extent of areal coverage of main categories of LULC in SWM forest reserve compared to the baseline status of 1970s. Generally, the total forest coverage in the area has been on a declining trend while cropland coverage has been on a continuously increasing rising to over seven times of the initial coverage. Grassland coverage has also been on an increasing trend up to the 2000s decade when the trend reversed. These variations are indeed an indication that the area experienced deforestation.

Table 1: Evolution of different LULC types over the South West Mau Forest from 1970s to 2020s relative to 1970s decade

	1970s	1980s		1990s		2000s		2010s		2020s	
1	2	3	4	5	6	7	8	9	10	11	12
LULC	Ha	Ha	%Var.	Ha	%Var.	Ha	%Var.	Ha	%Var.	Ha	%Vari.
Forest	73174.4	69353.4	-5.2	64272.4	-12.2	55945.5	-23.5	49638.0	-32.2	55368.8	-24.3
Grassland	8187.8	11008.9	34.5	13597.0	66.1	21832.0	166.6	12978.6	58.5	4288.6	-47.6
Cropland	2912.2	3912.2	34.3	6405.0	119.9	6496.9	123.1	21657.9	643.7	24617.0	745.3

3.2 Model Simulations

Figure 4 presents results of observed and model-simulated mean monthly surface water yields at Kiptiget RGS at the immediate downstream of South West Mau Forest. Based on the results of calibration, with the coefficient of determination (R^2 = 60%), the model performance was rated satisfactory (60), results show that observed and simulated water yields were in agreement. The model captured the patterns of monthly surface water yields quite well in all the months except August where the model indicated high flow while the observed indicated a low flow. This could be attributed to the fact that the model simulated flows follow a smoother curve than that of the observed flows leading a slight lag in the model simulated flows. The smoothing of the model simulated curve results from the model parameter estimations so that the model only estimates the flows. Overall, the model captured the high and low flows quite well indicating that the model could indeed be used to simulate stream flows in the area.

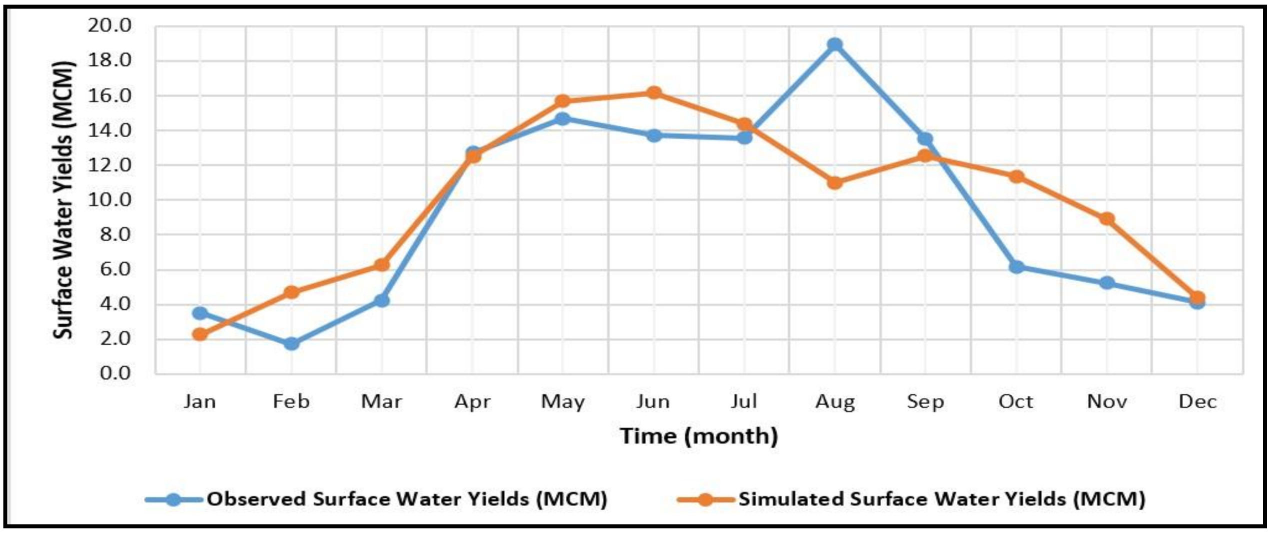

Figure 4: Comparison of seasonal variation of observed and simulated mean monthly surface water yields at Kiptiget RGS

Figure 5 presents a correlation of gauge-observed and model-simulated average monthly surface water yields. These results show that observed and simulated mean monthly surface water yields in the area are highly correlated (r = 0.81 and R^2 = 0.66). This is an affirmation that the model is suitable for the area of study and could therefore be used to simulate surface water yields.

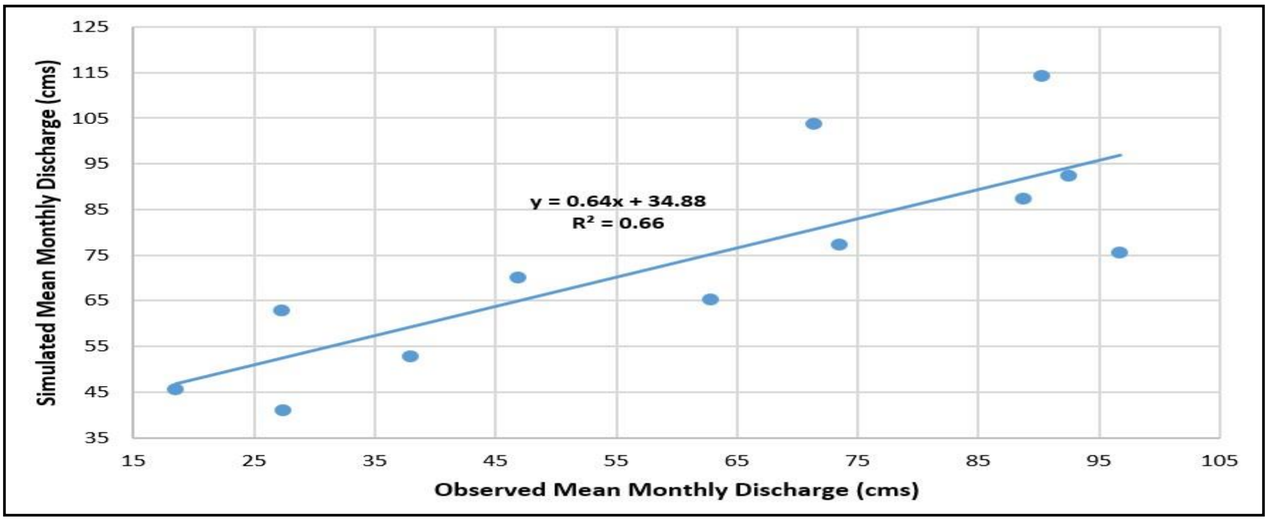

Figure 5: Correlation of mean monthly observed and simulated water yields (cms) at Kiptiget RGS

3.4 Impacts of Deforestation on Surface Water Yields

Figure 6 presents percentage variations in mean annual surface water yields under different LULC scenarios based on the 1970s decade baseline LULC scenario at Kiptiget RGS. These results show that as the forest coverage declined due to conversion to other uses, there was a progressive increase in surface water yields between 1970s and 2010s decades of up to 23%. This increasing trend in surface water yields was in line with the decreasing trend in forest coverage (Figure 2) where loss of natural forest cover is known to reduce infiltration and thereby causing more rainwater to reach the river system as direct surface runoff with very little of it going to groundwater recharge. In such circumstances flood incidences tend to increase during the wet seasons while low flows during the dry seasons progressively become lower due to the reduced groundwater component of streamflow. Therefore, it was concluded that deforestation of the area has led to enhanced surface water yields at a rate of 7.5% between the 1970s and 2010s decade. This could explain the increased incidents of floods in the basin as well as the surrounding areas in the recent decades.

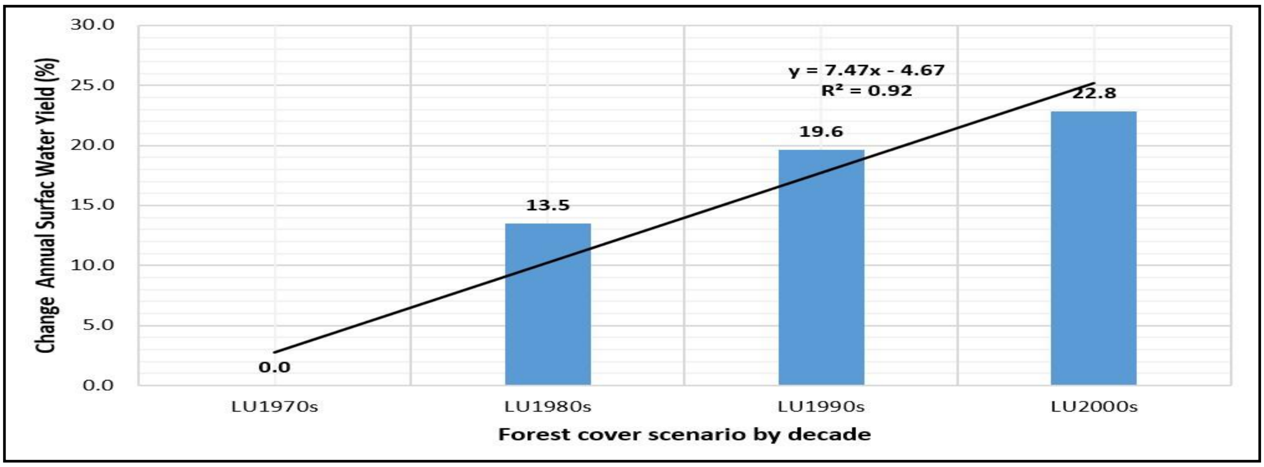

Figure 6: Variations in the mean annual surface water yields with deforestation relative to the 1970s baseline forest cover scenario

Given that the same climate data were used during all the simulations under different LULC scenarios, observed variations in surface water yields were ascribed to the changes in the level of forest coverage which tends to alter the hydrology of a catchment area. Further, given that the 1970s decade LULC scenario (LU70s) has the highest forest coverage while the 2000s decade scenario (LU00s) has the lowest coverage (Figure 2 and Table 1), it was clear that deforestation tends to increase annual surface water yields in the basin by about 7.5% per decade.

The observed increases in surface water yields resulting from deforestation may be attributed to reduced infiltration and evapotranspiration following deforestation of the watershed. While reduced evapotranspiration directly feeds into increasing the yields by reducing the volume of water that is lost back to the atmosphere, reduced infiltration leads to less soil and groundwater recharge and hence less storage during wet seasons. With less soil and groundwater storage the volume of water flowing in streams during the relatively dry seasons will decrease. This negates the gains of increased yields since less water will be available when it is needed most unless artificial storage reservoirs are availed. Therefore, increases in surface water yields with declining forest coverage are not sustainable as the reduction in infiltration rates tend to reduce the subsurface and groundwater flow components of streamflow that are key in sustaining surface water yields during the dry seasons.

Figure 7 presents regression of variations in annual surface water yields relative to those of 1970s on different levels of forest coverage to establish the relative changes in water yields resulting from unit changes in the level of deforestation. These results indicated that indeed annual surface water yields highly depend on the extent of the forest coverage. As the extent of deforestation increased, annual surface water yields also increased. A unit area deforested in the catchment increased annual surface water yields by about 0.9% of the 1970s baseline water yields. Essentially this increase in surface water yields is realised at the expense of groundwater recharge which eventually leads to reduced baseflow. Therefore, deforestation, which is attributable to about 87% of the increase in surface water yields ($R^2 = 0.87$) could explain the high frequency of flood incidents in this area.

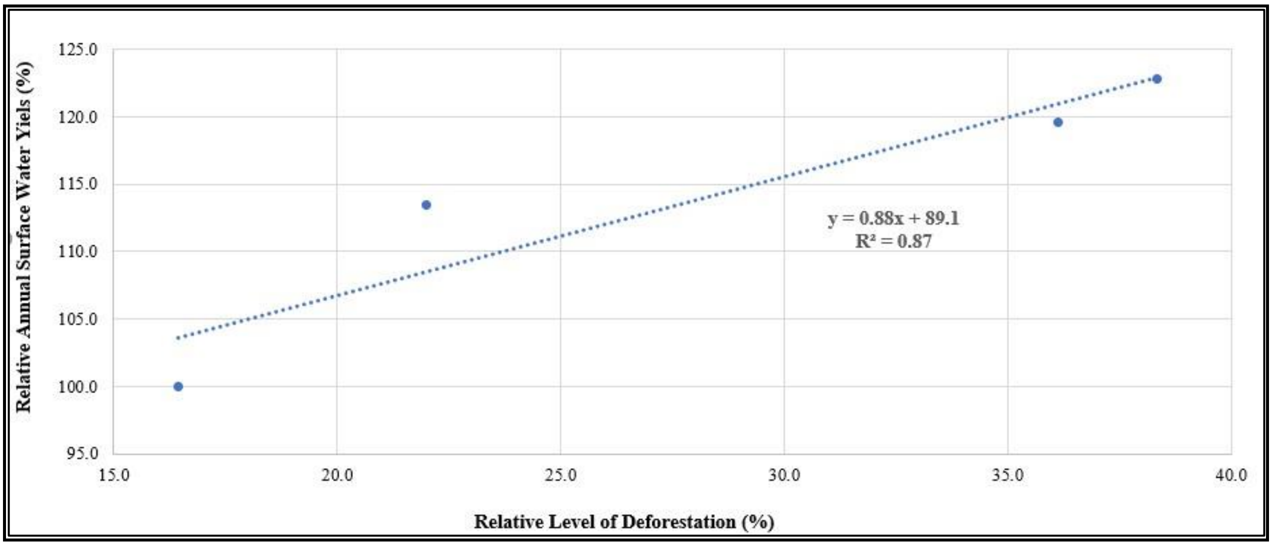

Figure 7: Effects of deforestation on surface water yields with deforestation accounting for 87% of the variations in surface water yields

3.6 Conclusion

The study has demonstrated that deforestation has reduced the stability of Mau Forest as a water tower and conservation of the forest will enhance its water holding capacity thereby ensuring a stable water supply to rivers emanating from it as a way of combating floods and low flows in the basin. Removal of natural forest cover and its subsequent replacement with other non-forest land uses has led to an increase in the amount of effective annual rainfall finding its way to the river system as direct surface runoff leading to high fluctuations in streamflow volumes between the wet and dry seasons. This is due to the reduced net capacity of soil and groundwater storage system. The increase in surface runoff raises the risk of flooding in the area following high magnitude rainfall events as has been witnessed in the area lately. With the reduced groundwater recharge as a result of reduced infiltration, the base flow of the river systems is expected to decrease with time. This is so because groundwater withdrawal as base flow is not matched by corresponding recharge during the wet seasons. We may therefore expect a higher frequency of flood incidents during the wet seasons accompanied by reduced dry season flows which will have a negative impact on the water supplies unless measures are taken to rehabilitate the forest.

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