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Influence of Tea Plantations, Forest and Mixed Farming on Stream Flow and Sediment Loads, Case of Sondu Miriu River Basin, Kenya

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Abstract

The changing patterns of land cover and land use in the tropical river basin over time are critical. The hydrological phenomena at basin and sub basin scale are affected positively or negatively by dynamics of the land cover and land use patterns. Hence identifying causes and driving factors aid in taking appropriate measures to avert the impacts. This study determined the influences of sub basins dominated by tea plantations, forests and agricultural land uses in terms of streamflow and sediment flux variability in Sondu Miriu River Basin in Kenya, East Africa. Field-based investigations were conducted through sampling of flow velocities, turbidity and TSSC obtained from existing River Gauging Stations established within the three sub basins. The sub basin dominated by mixed farming land cover exhibits high turbidity approximately 620 NTU and high levels of total suspended sediment concentration (TSSC) of the order of 630 mg/l in wet seasons. The turbidity levels and TSSC were low in sub basins dominated by forest and tea plantations with approximately mean value of 17 - 29 NTU and 0.019 g/l. The sediment loads in sub basin dominated by mixed farming in the pre planting season in January to February were about 900 tonnes/day higher than that in crop growing season. In sub basins dominated by forest cover and tea plantations, sediment loads were low ranging between 2 - 7 tonnes/day. The relationship between stream flows and area under tea plantations, forests and mixed farming ranged between R^2 of 0.025 and 0.16. Tea plantations and forests influence the stream flows and sediment yields in long term duration while in mixed farming variations were observed seasonally. The strong relationships between rainfall and stream flows at the sub basins ranging between R^2 of 0.84 and 0.97 revealed the significance of rainfall in hydrologic response of the Sondu Miriu River Basin.

Keywords

Sediment Loads, Stream Flows, Tea Plantation, Forest, Mixed Farming and Sondu Miriu

1. Introduction

Land cover and land use changes have been increasing with demands of social and economic growth. The dynamics of the hydrologic responses in a tropical river basin has been related to the changes occurring in the land covers and land uses in the sub basins. Forest land cover has been known to be important factor in the regulation of the hydrologic components of the river basins [1]. Existing theory indicates that forest land cover promotes sustainability of water accessibility by enhancing perennial flows in the sub basins. Conversion of forest land cover into other land uses affects the natural balance of the hydrologic components in the river basins [2]. At the same time challenges which are being faced as a result of decline in water quantity and quality have been linked to changes in the land cover and land uses [3]. Knowledge on the effect of land cover changes on stream flows and sediment yields is limited in the tropics compared to the temperate region. For example, study conducted in Western Europe, Southwest China and upper Yellow River showed that deforestation at the catchment level increases sediment flows and reduces stream flows [4] [5] [6] [7]. Most studies conducted in tropical river basins have not considered the effects of deforestation on river discharges and sediment yields. Therefore, conservation of forests has not been taken into account the important role forests play in the sustainability of the river discharges [8] [9].

The demands for socio-economic development in the tropical river basins such as Sondu Miriu in Western Kenya have led to expansion of the lands under tea plantations as the lucrative cash crops with reasonable returns. In the Sondu Miriu River Basin, the area under tea plantations has been increasing and this has led to significant reduction of the area of land forest cover in the upper and middle sub basins of the river basin. Similarity in canopy cover between tea plantations and forest cover has led to the assumptions that there are no significant differences in the hydrologic response of the two land covers. However, determination of the hydrologic response of river basins dominated by tea plantations and tropical forests has been limited due to lack of studies focused in Africa. The previous study conducted in East Usambara Mountain, Tanzania revealed that tea plants have effect on water quality especially in relation to oxygen levels affecting aquatic ecosystem [10] [11]. The dominance of tea plantations and tropical forests in the upper reaches of Sondu Miriu River Basin provided an opportunity to determine the relative impacts of tea plantations and tropical forests on stream flows and sediment discharges.

Studies conducted elsewhere have shown that deforestation of river basins leads to increased variability and or seasonality of stream flows and low water quality [12] [13] [14] [15] [16]. However, the conversion of forest land cover into other different land use has not been studied in Kenya to determine the possible effects of the land cover and land use change on the hydrologic response of the river basin. In the case of the Sondu Miriu River Basin deforested areas were replaced mostly by agricultural fields and settlements. The agricultural fields consist of different crops which have diverse effects on hydrological components. In this study all crop fields except tea plantations were considered into one cluster of mixed farming land cover. Now talk about what is known about influence of mixed farming on hydrologic response of river basins.

The equilibrium between sustainable water resources availability and growth in socio economic is critical especially in river basins with continuous population growth. Lack of data and knowledge on the impacts of the forest, tea plantation and mixed farming land covers on current and future state of water resources makes planning and decision-making difficult. Understanding the hydrologic response in the sub basins of the Sondu Miriu River Basin is also critical in identifying seasonal variations and long-term behaviour of stream flows and sediment fluxes in the Lake Victoria. The main objective of this study is therefore to determine the hydrologic responses of the tropical sub basins that are characterised by tea plantations, forests and mixed farming. The hydrologic response was determined in terms of changes in stream flows and sediment fluxes in tropical river basins of Africa.

2. Materials and Methods

2.1. Materials

2.1.1. Description of the Study Area

The Sondu Miriu River Basin is located in western region of Kenya with most of the headwaters are situated in Nakuru and Kericho Counties (**Figure 1**). The basin is situated within the latitude 0˚17' and 0˚53' South and longitude 34˚45' and 35˚45' East. It covers a surface area of about 3470 km^2 with an altitude ranging from 3000 m above sea level at the Mau Complex to about 1100 m above sea level at the shores of Lake Victoria [17].

2.1.2. Land Use and Climate

The Sondu Miriu River Basin is characterized by presence of various land covers and land uses. The main land covers in the basin are natural forest, man-made forest, tea plantations, scrubs, mixed farming. Prior to 1970s, the total area under forest in the Mau complex within the basin was approximately 420,000 hectares [18]. However following invasion of the basin for settlement and farming since 1970s and especially in the year 2000, the forest canopy has reduced by approximately 32% and the small patches of forest cover are now left in the central upper part of the basin [17].

The climate of the Sondu Miriu River Basin is characterized by bimodal rainfall within a given year hence by humid and semi humid climatic zones. The

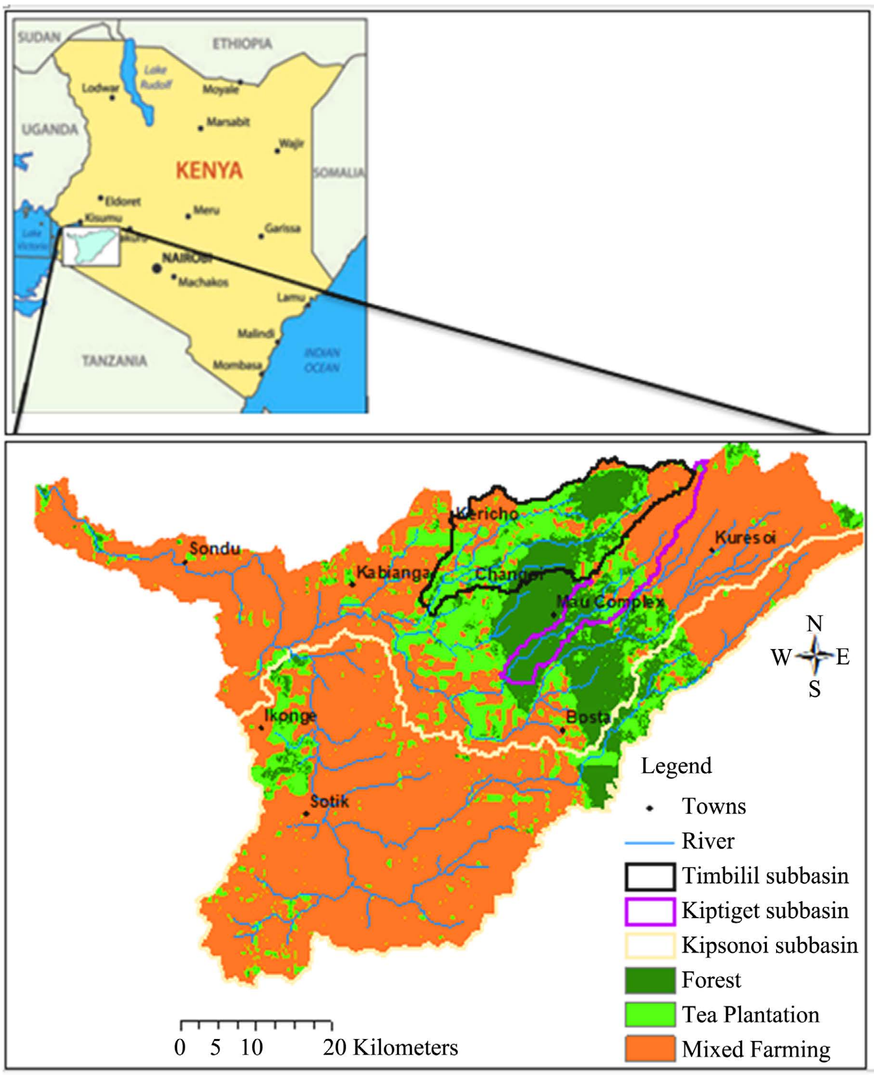

Figure 1. The location of sub basins in the Sondu Miriu River Basin in Kenya.

long rains occurs in the periods between April and July and short rains occurs in the period between October and December [19]. The upland zones receive mean annual rainfall of approximately 1800 mm per annum while lowland zones receive about 1500 mm per annum [16].

2.1.3. Hydrology and Drainage

In the Sondu Miriu River Basin, there are two main tributaries in the upper zone of the basin namely Kipsonoi and Yurith (**Figure 1**). The Kipsonoi tributary has its headwaters in Kuresoi in Nakuru County. The Timbilil sub tributary originates from Kuresoi and Mau forest in Kericho and flows through Kabianga area. The Kiptiget and Itare-Chemosit sub tributaries originates from Kuresoi and Mau forest and flows through Jamji area. The three tributaries converge at Kabianga tea estate to form Yurith tributary. The Kipsonoi and Yurith tributaries converge at Ikonge tea plantation. The total length of the Sondu Miriu River is approximately 190 km from its head to the shores of the Lake Victoria [17].

2.1.4. Topography and Soils

Sondu River Basin comprises of uplands at the upper catchments and low lands towards the shores of Lake Victoria. Mau Escarpment that occurred due to formation of the rift valley characterizes the upstream part of the basin. The maximum altitude of the river basin is about 3000 m above sea level. The lowest elevation in the downstream zone of the basin is about 1100 m above sea level [16]. The main soil type found in sub basins of the Sondu Miriu River Basin are nitisols, andosols, lithosols, greyzems, cambisols, arenosols, phaeozems, planosols, rankers, regosols, vertisols, xerosols and luvisols [20].

2.1.5. Location of Stations and Sampling

The primary data collected comprises of river discharges, TSSC, sediment loads and turbidity from July 2020 to June 2021. These data were obtained from the field in the sub basins dominated by tea plantations, forests and mixed farming land covers. Sampling stations were River Gauging Stations RGS 1JA02 located at −0.55480 S, 35.25844 E in the Kiptiget sub basin, RGS 1JC02 located at −0.46250 S, 35.17917 E in the Timbilil sub basin, RGS 1JF08 located at −0.51463 S, 35.08010 E in the Kipsonoi and RGS 1JG05 located at −0.39664 S, 35.01698 E near Sondu Market at the downstream of the Sondu Miriu River Basin. Spatial land use and land cover data was obtained for the 1975 to 2020 from USGS database.

2.2. Methods

2.2.1. Stream Flow and Rainfall Data

River discharges were measured in the period between July 2020 and June 2021. Velocity measurements were carried out using Acoustic Doppler Current Profiler (ADCP) device (Sontek ®Argonaut SW) and propeller current meter Seba model. The current meter was placed in the vertical depths along river cross sections to measure velocities [21]. The velocities were measured in two-point depth of the vertical such as 20% and 80% from the water surface towards the stream bed average velocity was used to determine the stream flows using Equation 1. Secondary stream flow and rainfall data from 1960 to 2020 was obtained from Government of Kenya such as Water Resources Authority, Ministry of Water, Sanitation and Irrigation and Kenya Meteorological Services.

$$Q = \left\{ \left(q_1 = v_{av1} \left(\frac{w_1}{2} \right) d_{av1} \right) + \cdots + \left(q_n = v_{avn} \left(\frac{w_n}{2} \right) d_{avn} \right) \right\} \tag{1}$$

where:

Q the stream discharge (m^3/s), q discharge in stream cross section (m^3/s), v_{av} the average measured velocity at 20%, 60% and 80% depths (m/s), w the width of the sub section between verticals of stream cross section (m) and d_{av} the average measured percentage depths of the verticals within the sub section of stream cross section (m).

2.2.2. Turbidity and TSSC Measurements

The water samples obtained at different sub sections of the stream cross section were collected to turbidity at each sub basin using calibrated multiprobe meter. Also, water samples were collected in 1 litre sampling bottles and placed inside the sample storage box and transferred to Kenya government water quality laboratory for analysis [22].

2.2.3. Laboratory Analysis

In the laboratory collected water samples were analysed in the laboratory using American Public Health Association (APHA) standard water quality procedures [22]. Whatman GF filters was weighed using a digital scale (Wf) and activated to check tears and holes before using for filtering the samples. The sampled water from each sub basin collected from different width segments were mixed to obtain the total volume (V). The filters were attached into a funnel cup and the water samples were filtered. The retained residues in the filters were placed in 8" × 8" glass pan and dried in an oven for at least 24 hours at temperature of 103˚C - 105˚C [22]. The dried sediments in a filter were weighed using a digital balance (Wc) and the total weight of the sediments per sampling site at a given period of time was determined. The $TSSC$ was obtained by determining the difference between weight of filter with dried debris and weight of empty filter (Equation (2)). The annual sediment loads were computed at monthly temporal scale using Equations (3) and (4).

$$TSSC = \frac{Wc - Wf}{V} \times 10^6 \tag{2}$$

$$S_l = \left\{ \left(\left(TSSC_1 \times Q_1 \right) \times 8.46 \right) + \cdots + \left(\left(TSSC_n \times Q_n \right) \times 8.46 \right) \right\} \tag{3}$$

$$S_l = \left(\sum_i^n TSSC_i \times Q_i \right) \times 8.46 \tag{4}$$

where:

$TSSC$: the total suspended solids Concentration (mg/l),

Wc: the weight of debris and filter (mg),

Wf: the weight of the filter (mg) and

V: the volume of the water sample (litres),

S_l: the annual sediment yield (tonnes/annum),

$TSSC_i$: the monthly TSSC data in mg/l,

n: the nth month of the data collected and

Q_i: the average monthly stream discharges (m^3/s),

A: the area of the sub basin (Hectares) [23].

2.2.4. Data Analysis

The discharge, sediment load, TSSC, turbidity and rainfall data collected from the sub basins dominated by tea plantation, forest and mixed farming land covers and land uses were processed and analysed using statistical approaches. Time series, graphs, maps and tables were used to present visualized data for interpretation [24] [25].

3. Results and Discussion

3.1. Results

3.1.1. Effects of Sub Basins with Dominant Land Uses on Stream Flows

1) Effects of Timbilil sub basin dominated with tea plantations on stream flows

The long-term trends of stream discharges in the sub basin dominated by tea plantations showed that changes in the area under tea plantations affects the river discharges. For example, in the period between 1988 and 1998, the area under tea plantations increased by 11.1 km^2 and the increase of river discharges by 10.3 m^3/s was observed. In the period between 2008 and 2017, similar trend was observed with reduction of area under tea plantation by 2 km^2 and decrease of stream discharges by 6 m^3/s (**Figure 2**). The relationship between stream flows and area under tea plantations was positive with $R^2 = 0.075$ and correlation r of 0.27. Further strong positive relationship between rainfall and stream flows were observed with R^2 of 0.96 and r value of 0.98. These confirmed that the rainfall has significant influence on the changes in the stream discharges in the sub basin apart from the land cover changes. The flow duration analysis revealed that the stream discharge that equalled or exceeded 70% of the time was 8.1 m^3/s while at 95% was 5.7 m^3/s indicating that Timbilil River is perennial. The mean discharge was 10.8 m^3/s (**Table 1**).

2) Effects of the Kiptiget sub basin dominated by forest land cover on the stream flows

The time series of the stream discharges in the sub basin dominated by the forest were compared changes in the area of forest land cover in the period 1975-2020. In the period between 1975 and 1986, the area under forest cover increased by 7.6 km^2, the stream discharges decreased by 4.6 m^3/s and rainfall decreased by 280 mm. In the period between 1988 and 2001 an increase in the stream discharges by 4.5 m^3/s, rainfall increased by 340 mm while area under

Table 1. The magnitude of stream flows in the sub basins with dominant land cover and land use.

Sub basins	Maximum River Discharge (m^3/s)	Minimum River Discharges (m^3/s)	Mean river discharges (m^3/s)	River discharges in 50% flow duration	Relationship between area of land cover and river discharge (r)	Remarks
Sub basin dominated by Tea Plantations	17.4	5.7	10.8	10.7	0.27	Moderate water yield, low runoff generated, moderate variability
Sub basin dominated by forest cover	7.5	2.1	4.5	4.5	−0.41	Low water yield, low surface runoff, high infiltration, low variability
Sub basin dominated by mixed farming land use	57.2	10.9	32.4	30.2	0.16	High water yield, high surface runoffs, high variability

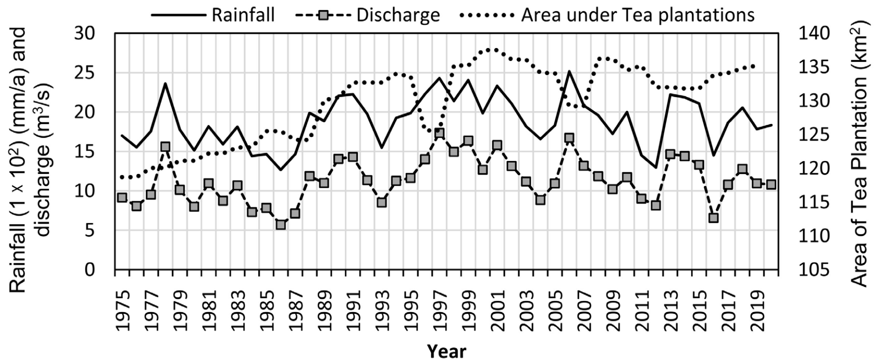

Figure 2. Stream flow, rainfall and tea plantation in the Timbilil sub basin in the period between 1975 and 2020.

forest cover decreased by 10.8 km^2 (**Figure 3**). Despite changes of the area under forest cover with stream flows occurred in similar periods, it was an insignificant influence. The relationship between stream discharges and area under forest land cover was negative with r value of −0.41 and R^2 value of 0.16. The negative relation was due to increase of stream discharges as the land under forest cover decreases through deforestation and vice versa. The response of rainfall event in the deforested land is surface runoffs and reduced infiltration leading to increase in the stream flows during rainy days. While the relationship between rainfall and stream flows were strong with R^2 of 0.94 and r of 0.97. This led to assumption that rainfall is the main factor influence the stream flows in the sub basin. The flow duration curve has gentle slope which is typical of perennial river systems. The river discharges in 90% of the time in the sub basin are approximately 2.8 m^3/s. The 70% of the time are about 3.5 m^3/s. The maximum stream discharge was 7.48 m^3/s and minimum stream discharge was 2.02 m^3/s. The mean stream discharge was 4.48 m^3/s (**Table 1**).

3) Effects of the Kipsonoi sub basin dominated by mixed farming on stream flows

The area under mixed farming in the sub basin dominated by mixed farming showed direct relationship with stream discharges. The relationship between river discharges and area under mixed farming was positive but weak with coefficient of determination R^2 of 0.025 and correlation coefficient r value of 0.15. This indicated that changes in the area under mixed farming contribute to only 15% of the variations of river discharges. The decline in the area under mixed farming by 101 km^2 decreased stream discharges by about 6 m^3/s in the period between 1975 and 1986. In the same period the rainfall decreased by 142 mm. Sequentially in the period between 2001 and 2013, the area under mixed farming decreased by 17 km^2 while the stream discharges and rainfall reduced by 44.7 m^3/s and 167 mm respectively (**Figure 4**). In this period 2001-2013, a significant change in the stream flows were observed without major changes in the area under mixed farming. This showed that other factors contribute to changes in stream flows such as rainfall. The relationship between rainfall and stream flow

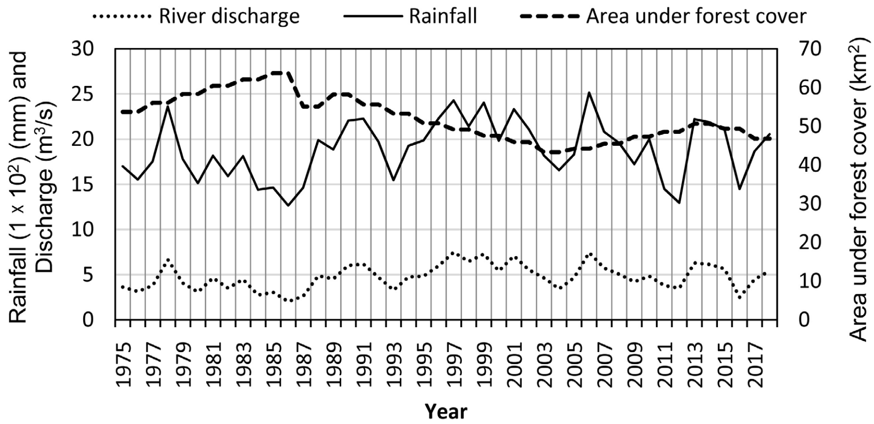

Figure 3. Stream discharges and forest land cover in the Kiptiget sub basin in the period1975-2021.

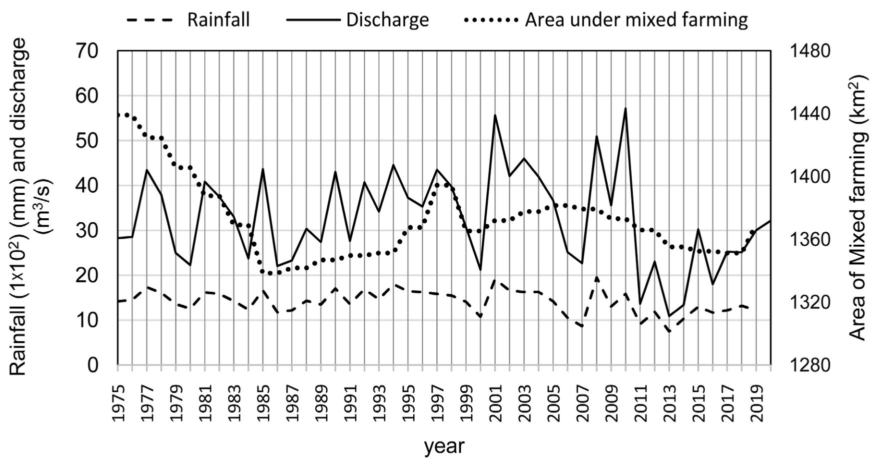

Figure 4. Mixed farming and stream discharges in the Kipsonoi subbasin in the period 1975-2020.

was R^2 of 0.84 and r of 0.96. The peak stream discharges return period was approximately 10 years. The maximum stream discharge in the sub basin was 57.2 m^3/s, minimum stream discharge of 10.9 m^3/s and the mean stream discharge of 32.4 m^3/s was experienced in the period between 1960 to 2020 (Table 1).

3.1.2. Effects of the Sub Basins with Dominant Land Covers and Land Uses on Sediment Flux

1) Effects of Timbilil sub basin dominated by tea plantations on sediment flux

Turbidity: The turbidity in the sub basin dominated by tea plantation was high during the short rainy seasons and was low during dry seasons. During the rainy season (short rains) turbidity levels ranged between 36.17 and 95 NTU while during the long rains turbidity were relatively lower ranging between 18.5 and 21.5 NTU (see Figure 5). The average turbidity level in the sub basin was approximately 29.5 NTU (see Table 2). The relationship between the turbidity and river discharges was positive but very weak with R^2 of 0.0036 and r value of −0.06. This shows that river discharges do not have significant effects on water

Table 2. Magnitudes of TSSC, turbidity and sediment yield in sub basins dominated by different land uses.

Sub basins	Parameter	Maximum	Minimum	Mean	50%	Remarks
Sub basin dominated by tea plantations	TSSC (g/l)	0.04	0.01	0.019	0.0167	Low TSSC
	Turbidity (NTU)	95	15.2	29.5	21.5	Moderate turbidity
	Sediment (tons/day)	14.5	1.02	7.05	6.52	Low sediment load
Sub basin dominated by forest cover	TSSC (g/l)	0.028	0.007	0.019	0.02	Low TSSC
	Turbidity (NTU)	27	4.3	17.4	18.2	Low turbidity levels
	Sediment (tons/day)	8.3	0.4	4.02	2.8	Low sediment load
Sub basin dominated by mixed farming	TSSC (g/l)	0.62	0.056	0.164	0.1	High TSSC
	Turbidity (NTU)	637	71	151.4	91	High turbidity levels
	Sediment (tons/day)	952	31.9	169.1	76.4	High sediment load
Combined land cover Sondu Miriu Basin	TSSC (g/l)	0.26	0.047	0.104	0.08	High TSSC
	Turbidity (NTU)	231	60	85.1	68	High turbidity levels
	Sediment (tons/day)	631.5	75.5	227.1	170.4	High sediment load

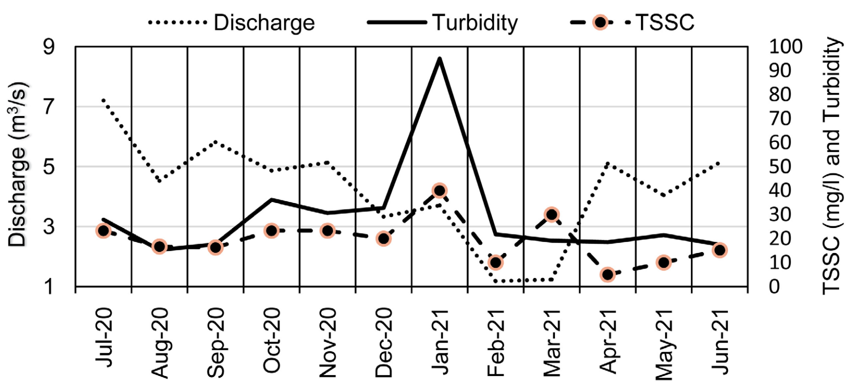

Figure 5. Turbidity, TSSC and stream discharge in Timbilil sub basin dominated by tea plantations (2020-2021).

turbidity in the sub-basin. This could be due to low surface runoffs and well protected soil surface by tea plantations from soil erosion causing minimal changes in turbidity during high flow periods.

Total Suspended Solids Concentrations (TSSC): The TSSC was high during the rainy seasons especially in the period between October 2020 and January 2021 ranging between 0.020 g/l and 0.040 g/l. At the onset of the long rainy season particularly in March 2021 the TSSC value of 0.03 g/l was observed. However, during dry and low flow seasons, TSSC ranging between 0.005 g/l and 0.015 g/l (Figure 5). The mean TSSC in the sub basin was 0.019 g/l (Table 2). The relationship between TSSC and river discharges showed negative relationship with correlation r of −0.093 and coefficient of determination R^2 of 0.0087. This showed that tea plantations reduce sediment transport. The relationship between TSSC and turbidity showed positive response with coefficient of determination R^2 of 0.56 and correlation r of 0.74. This showed that about 56% of the suspended sediments interfere with water clarity. Hence the sub basin is characterized by the water of low TSSC and turbidity.

Sediment loads: The sediment flux in the sub basin dominated by tea plantation revealed that sediment loads increase in rainy seasons. During the rainy season, the highest sediment load recorded was 14.5 tonnes/day while the lowest sediment load of 1.02 tonnes/day was observed in dry season. The average sediment loads in the sub basin was 7.05 tonnes/day (Table 2). A positive relationship with R^2 of 0.4 and r of 0.65 was observed between stream flows and sediment loads. This shows that the variations of sediment load were due to variations in stream flows in the sub basin. The low magnitude of sediment load indicates that soil erosion within the tea plantations is minimal. The relationship between turbidity and sediment loads had R^2 of 0.294 and correlation r of 0.54. While the relationship between TSSC and sediment loads was positive relation with coefficient of determination R^2 was 0.94 and correlation r of 0.97 (Figure 6). This showed that about 29% of the suspended sediments caused turbidity while 71% are suspended sediments which interfere with the clarity of water such as debris from logs and humus from leaves.

2) Effects of Kiptiget sub basin dominated by forest land cover on sediment flux

Turbidity: The turbidity levels in the sub basin dominated by the forest land cover were high in wet season and low in dry periods. In short rainy season (September-December) turbidity ranged between 15 NTU and 27 NTU while in long rainy season (May-July) it ranged between 18.2 NTU to 18.9 NTU. In dry periods turbidity levels were generally low as they ranged between 4.3 NTU to 6.9 NTU (Figure 7). The mean turbidity observed was 17.4 NTU (see Table 2). The relationship between turbidity and river discharges in the sub basin was positive with coefficient of determination R^2 of 0.54. The high positive correlation r of 0.73 showed that increase in stream flows raises the turbidity levels It must be noted that the turbidity levels in the sub basin are much lower than those reported in the Upper Athi river basin which reaches 1000 NTU [26]. There are also much lower than those reported in the Upper Tana Basin [27].

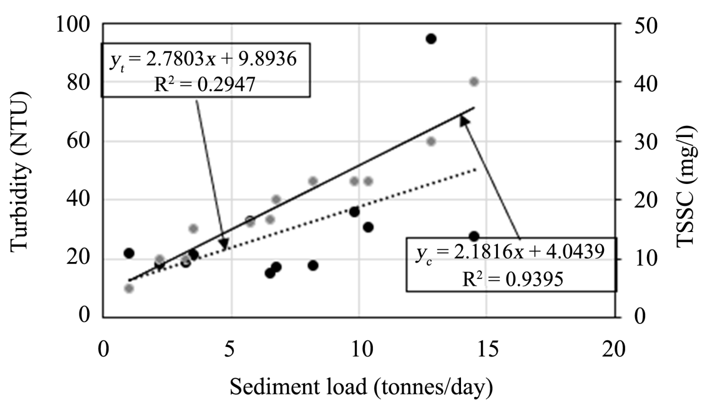

Figure 6. Relationship between sediment load, turbidity and TSSC in the Timbilil sub basin dominated by tea plantations in the period 2020-2021.

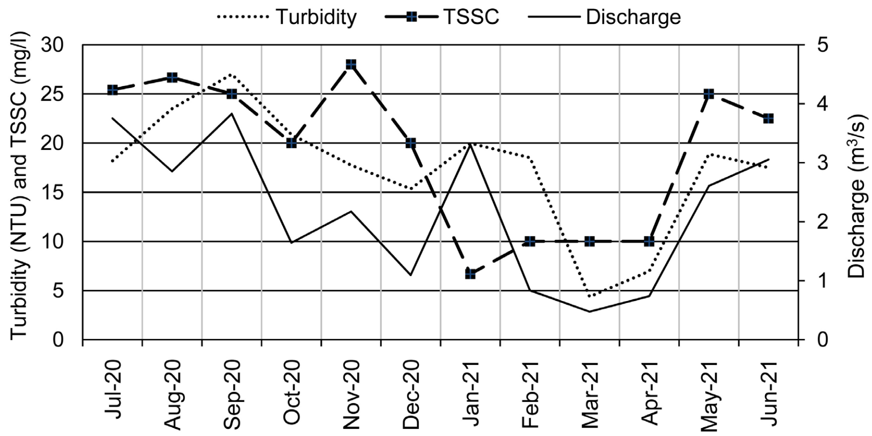

Figure 7. Turbidity, TSSC and stream discharges in Kiptiget sub basin in the period 2020-2021.

Total Suspended Solids Concentrations (TSSC): The TSSC in the sub basin dominated by the forest cover showed similar pattern with the pattern of the river discharges. During the short-rainy season, the TSSC observed in the sub basin ranged between 0.01 g/l and 0.028 g/l. Further in long rainy season, the TSSC ranged between 0.01 g/l and 0.025 g/l. During the dry periods, the TSSC in the sub basin were relatively much lower as they ranged between 0.006 g/l and 0.01 g/l (**Figure 7**). The mean TSSC in the sub basin was 0.019 g/l (see **Table 2**). The TSSC levels obtained in the sub basin were much lower than 1.5 g/l to 2.3 g/l recorded in the Upper Athi river and Upper Tana River basin [26] [27]. The relationship between TSSC and river discharges showed positive correlation r of 0.54 and the coefficient of determination R^2 was 0.29. This confirmed that in dry period very low suspended solids are transported in the river system in the sub basin. The relationship between TSSC and turbidity showed positive relation with correlation r of 0.56, and coefficient of determination R^2 of 0.3. Similar to results obtained in the sub basin dominated by tea plantations, this sub basin showed that not all suspended solids in water column in the streams causes' turbidity.

Sediment loads: Sediment loads in the sub basin dominated by forest land cover showed that in long rainy season the sediment loads observed ranged between 5 tonnes/day to 8 tonnes/day. The sediment loads generated in short rainy season ranged 1.9 tonnes/day and 5.6 tonnes/day. In dry months, the sediment loads observed ranged between 0.4 tonnes/day and 1.9 tonnes/day. The mean sediment load in the sub basin was 4.02 tonnes/day (**Table 2**). Comparing the patterns of the sediment loads and the discharge in the sub basin, it showed that sediment loads increase with the increase in the discharges. The total annual sediment load was 1.840 tonnes/annum. This was much lower than approximately 250 - 366 tonnes/year reported in the sub-basins draining the Upper Athi river basin in eastern Kenya [26]. The low sediment loads in the sub basin was due to reduced soil erosion in the forest land cover. The relationship between sediment loads and the river discharges showed positive relation with the correlation r of

0.86 and coefficient of determination R^2 of 0.74. The relationship between the sediment loads and turbidity showed positive relation with correlation r of 0.67 and coefficient of determination R^2 of 0.44 (**Figure 8**). Further the relationship between sediment loads and TSSC showed positive relation with correlation r of 0.85 and coefficient of determination R^2 of 0.73. This high positive correlation between sediment loads and turbidity and TSSC showed that the surface runoffs transport sediments into the water system in the sub basin. At the same time the suspended sediments increase turbidity.

3) Effects of Kipsonoi sub basin dominated by mixed farming land uses on sediment yields

Turbidity: The seasonal variability in turbidity in the sub basin dominated by mixed farming observed were the post-harvest period (September-December), pre planting period (January-March) and crop growing season (April-August). The turbidity in the post-harvest period ranged between minimum of 71 NTU and maximum of 112 NTU (**Figure 9**). The mean turbidity for the post harvest season was 85 NTU. In the pre planting season it was noted that the turbidity levels ranged between minimum of 91 and maximum of 637 NTU. These variations were caused by short rains experienced in January and dry periods in March and February. The mean value was 335 NTU. In the crop growing season the turbidity levels ranged between minimum of 80 and maximum of 115 NTU (see **Table 2**). In this period the stream flows were high due to long rainy season while turbidity was low due to growing crops growing in the agricultural fields which reduced soil erosion. The relationship between turbidity and river discharge in the sub basin showed positive response with coefficient of determination R^2 of 0.08 and correlation r of 0.28. This showed that turbid water in the sub basin is not only caused by surface runoffs but there could be instream activities which generates turbid water during low flow periods.

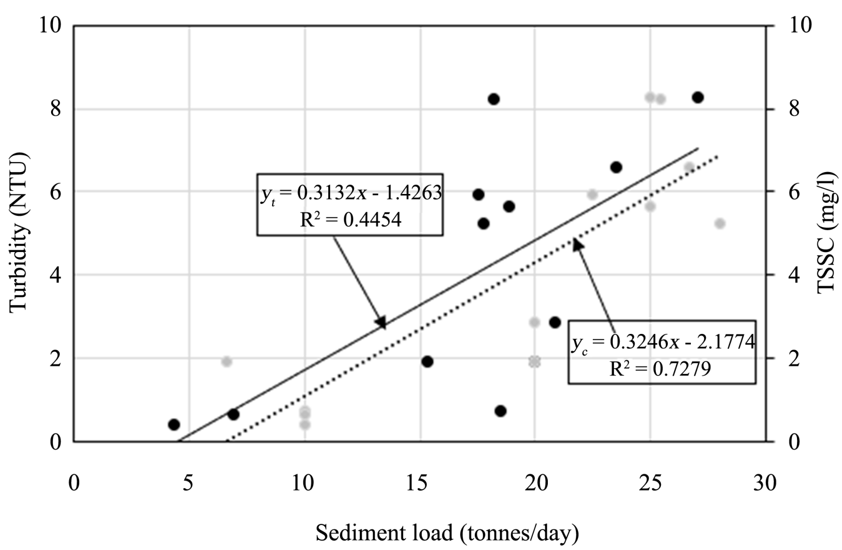

Figure 8. Relationship between sediment loads, turbidity and TSSC in the Kiptiget sub basin in the period 2020-2021.

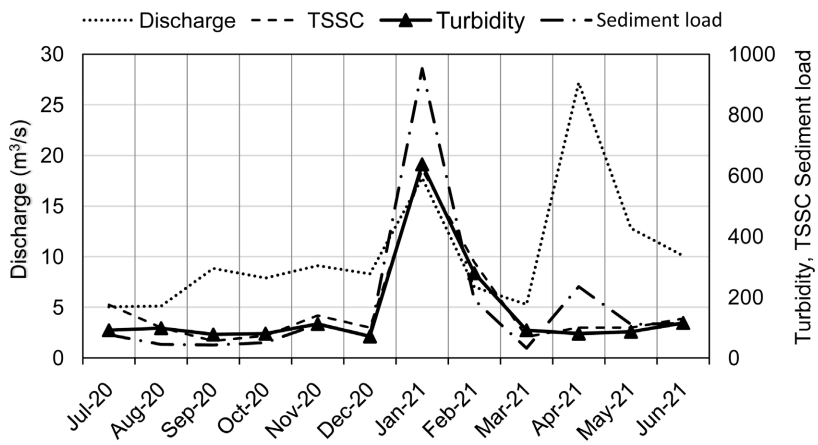

Figure 9. Turbidity, TSSC and stream discharges in the Kipsonoi sub basin in the period 2020-2021.

Total Suspended Solids Concentrations (TSSC): The TSSC in the sub basin dominated by mixed farming showed high variability in the post-harvest, pre-harvest and active crop growing seasons. This variability had similar pattern with the river discharges (Figure 9). In the post-harvest period, the TSSC ranged between 0.056 g/l and 0.140 g/l. In the pre-planting period, the TSSC ranged between of 0.07 g/l and 0.620 g/l. In the crop growing season the TSSC in the sub basin ranged between 0.1 g/l and 0.175 g/l. The maximum TSSC observed in the sub basin was 0.62 g/l and minimum of 0.056 g/l was observed. The mean observed TSSC in the sub basin was 0.165 g/l (see Table 2). The relationship between TSSC and the river discharges was positive but weak with the coefficient of determination R^2 value of 0.07 and correlation coefficient r value of 0.26. The weak positive relation between TSSC and river discharges could be due to instream activities which causes instream erosion. The relationship between TSSC and turbidity showed high positive relation with coefficient of determination R^2 of 0.97 and the correlation r of 0.98. This showed that the main cause of turbid water in the sub basin was suspended sediments from the upper parts of the sub basin. The TSSC duration curve (Figure 10) showed that at less than 5% of the time, the TSSC was greater than 0.60 g/l. Further in the time greater than 95% the TSSC was found to be less than 0.07 g/l.

Sediment loads: The sediment loads observed in the sub basin dominated by mixed farming land use showed that the peak sediment yield occurred in pre planting season. The sediment loads in the sub basin during pre-planting season ranged between 190 tonnes/day and 952 tonnes/day. In the post harvesting season, the sediment loads ranged between 42 tonnes/day and 110 tonnes/day. During crop growing periods sediment loads observed ranged from 31 tonnes/day to 113 tonnes/day. The maximum sediment loads observed in the sub basin was 952 tonnes/day and minimum sediment load of 31 tonnes/day. The mean sediment load in the sub basin observed was 169.1 tonnes/day (Table 2). It was also observed that stream discharges increased with the rise in the

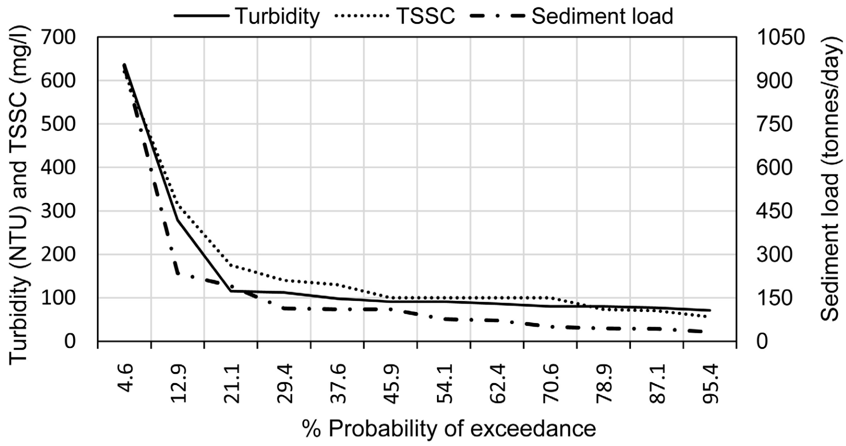

Figure 10. Turbidity duration curve in the Kipsonoi sub basin in the period 2020-2021.

sediment loads in the post harvesting and pre planting season while in the crop growing season rise in the stream discharges to 27 m^3/s could not increase sediment loads (**Figure 9**). The relationship between sediment loads and river discharges in the sub basin showed positive relation with R^2 of 0.27 and the correlation coefficient r of 0.52. Comparing the relationship between sediment loads and TSSC showed that most suspended solids were sediments. This confirmed with the high values of R^2 of 0.87 and correlation r of 0.93. Further high relationship between sediment load and turbidity showed high positive relation resulting in R^2 of 0.904 and correlation r of 0.95. This showed that turbid water in the Kipsonoi River more than 95% caused by suspended sediments. The sediment load duration curve (**Figure 10**) showed that in less than 5% of the time in the sub basin the sediment loads were more than 950 tonnes/day. Also, the sediment loads at 50% and 70% were 76 tonnes/day and 50 tonnes/day respectively. In more than 95% of the time in the sub basin the sediment loads were less than 32 tonnes/day.

3.2. Discussion

The results of this study showed that changes in the land cover and land use have impacts on stream flows and sediment flux in the long term. However, in the short-term rainfall was observed to be the main contributor of seasonal variations in the stream flows in the sub basins dominated by tea plantations, forest and mixed farming. Previous study conducted in East Africa Montane areas reported that thick canopy vegetation reduces overland flows and increases vertical movement of water through soil profile into the ground [18]. The observation was similar to the observation of this study where the negative relationship was established between forest cover and stream flows were observed. The low relationship between stream flows and sediment loads, turbidity and TSSC in the sub basins under forest and tea plantations cover showed that lateral flows and base flows contributes more to stream flows than the surface runoffs. This showed that afforestation and reforestation in an integrated manner can bring positive response to stream discharges especially base flow component that sustains the stream discharges both in wet and dry seasons. This is consistent with the findings of the study conducted in upper Blue Nile sub basins that showed that expansion of tropical forest leads to positive response to stream flows [28]. These revealed that tea plantations and forests cover increase stream flow and ensures sustainable stream flows. On contrary, the sub basin under mixed farming portrayed high stream flows which were believed to be mainly contributed by surface runoffs than base flows volumes especially during high rainfall periods (**Table 1**). Immediate response of rainfall received was observed in the stream networks of the Kipsonoi sub basin dominated by mixed farming with lagging time of less than six hours. In Gojeb and upper Baro River Basins River Basin it was noted that expansion of the area under mixed farming increase of stream flows through surface runoffs [15] [29]. These results showed that mixed farming land covers in the river basins generates high surface runoffs and frequent peak discharges hence raising annual average stream discharges. Therefore, deforested areas can be reinstated in an integrated manner for effective sustainable management of water resources [30].

Seasonal variations in the stream discharges, turbidity, TSSC and sediment loads were observed in the sub basin dominated by tea plantations, forests and mixed farming land covers and land uses. During dry periods the turbidity and TSSC recorded low values while high turbidity and TSSC rates observed during the rainy seasons. The seasonal variations in turbidity levels and sediment concentrations in wet and dry seasons showed that inflow of turbid water enters the river system through surface runoffs. At the onset of rainy season and during short rainy days suspended sediments transported into the river system increases but as rainy days prolong the quantity of sediments transported into the river system reduced. This clearly showed that soil erosion is minimal in tea plantations areas and most likely humus from the base of the tea trees and other loose soils and debris on the riparian lands constitute the suspected sediments transported in the Timbilil sub basin. This was confirmed by negative relationship between turbidity levels and stream discharges mostly in short rainy season. During long rainy periods it was suspected to result in dissolving decayed humus, soluble fertilizers, herbicides and pesticides. This assumption was supported by the low relationship obtained between turbidity and sediment loads in the sub basin. The difference between the relationship in turbidity with stream discharges in the Timbilil and Kiptiget sub basins was attributed to the upstream farming activities in the Kiptiget sub basin that increases transfer of suspended sediments from farms into the stream networks. Further it was noted that sediment loads observed in the sub basins dominated by tea plantations and forests cover was low and agreed with the previous study conducted in some fields in Kabianga that forest cover generates low total suspended sediments [23]. The relationship between turbidity and TSSC observed in the sub basin dominated by mixed farming was high and significant compared to the sub basins dominated by tea plantations and forests. This is in consistent with previous studies which showed significant relationship between turbidity and TSSC in mixed farming fields [26] [31] [32] [33].

The seasonal variability in turbidity, TSSC and sediment generation was observed in the Kipsonoi sub basin dominated by mixed farming. High turbidity levels, TSSC and sediment loads occurred during pre-planting season when fields were being prepared through ploughing exposing soils to erosion by surface run offs. In the planting season low turbidity, TSSC and sediment loads were observed due to soil protection by crops growing in the fields. This was observed in the months of April to July. These observations are in consistent with previous studies done in Gilgel Gibe River Basin where high turbidity, TSSC and sediment flux occurred mixed farming areas [34]. The post harvesting season showed turbidity, TSSC and sediment loads lower than pre planting season. This was attributed to the farm residues which protects the soils and reduces soil erosion. The seasonal variability in the sub basins dominated by different land uses showed that pre planting season (January to February) the sub basins experience high levels of turbidity and TSSC. These observations were in consistent with previous studies conducted in Tana River Basin, Kabianga and Itare sub basins [18] [23] [35] [36] [37]. Comparison between upper zones and lower zones of the Sondu Miriu River Basin showed that high sediment loads occurred in all parts of the river basin during pre-planting season. This was in consistent with the results reported in Upper zones of Athi River where significant relationship between stream discharges and sediment loads was observed [26]. The different land uses and land covers in the upper zone of the Sondu Miriu River Basin showed that turbidity, TSSC and sediment yields were low in the sub basins dominated by the forest cover and tea plantations compare to levels in the sub basin dominated by mixed farming. This variation was attributed to the ability of the land cover to protect sediment transport from the catchment areas.

4. Conclusion

Land cover and land use changes in Sondu Miriu River Basin have impacts on the hydrologic responses. Expansion of tea plantations and forests land cover increases base flows, reduces surface runoffs and enhances sustainable stream flows. But in the mixed farming land cover high surface runoffs were observed which in turn might cause perennial rivers to be seasonal by significantly affecting the base flow. This study also showed the seasonal variations in the sediment loads generated in the Timbilil, Kiptiget and Kipsonoi sub basins. During rain periods especially onset days the turbidity, TSSC and sediment loads observed were high in sub basin dominated by tea plantations and forest cover while in mixed farming land cover was high during rainy and pre planting seasons. The tea plantations and forest cover were found to be suitable land covers which enhance good water quality and sustainable flows in the river basin.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Guzha, A.C., Rufino, M.C., Okoth, S., Jacobs, S. and Nóbrega, R.L.B. (2018) Impacts of Land Use and Land Cover Change on Surface Runoff, Discharge and Low Flows: Evidence from East Africa. *Journal of Hydrology*: *Regional Studies*, **15**, 49-67. https://doi.org/10.1016/j.ejrh.2017.11.005

[2] Chandlera, K.R., Stevensa, C.J., Binleya, A. and Keith, A.M. (2018) Influence of Tree Species and Forest Land Use on Soil Hydraulic Conductivity and Implications for Surface Runoff Generation. *Geoderma*, **310**, 120-127. https://doi.org/10.1016/j.geoderma.2017.08.011

[3] Tundu, C., Tumbare, M.J. and Onema, J.M.K. (2018) Sedimentation and Its Impacts/Effects on River System and Reservoir Water Quality: Case study of Mazowe Catchment, Zimbabwe. *Proceedings of the International Association of Hydrological Sciences*, **377**, 57-66. https://doi.org/10.5194/piahs-377-57-2018

[4] Bussi, G., Dadson, S.J., Prudhomme, C. and Whitehead, P.G. (2016) Modelling the Future Impacts of Climate and Land-Use Change on Suspended Sediment Transport in the River Thames (UK). *Journal of Hydrology*, **542**, 357-372. https://doi.org/10.1016/j.jhydrol.2016.09.010

[5] Liu, Y., Wand, S., Qioa, Z., Wang, Y., Ding, Y. and Miao, C. (2019) Estimating the Dynamic Effects of Socioeconomic Development on Industrial SO_2 Emissions in Chinese Cities Using a DPSIR Causal Framework. *Resources*, *Conservation and Recycling*, **150**, Article ID: 104450. https://doi.org/10.1016/j.resconrec.2019.104450

[6] Bierschenk, A.M., Muller, M., Pander, J. and Geist, J. (2018) Impact of Catchment Land Use on Fish Community Composition in the Headwater Areas of Elbe, Danube and Main. *Science of the Total Environment*, **652**, 66-74. https://doi.org/10.1016/j.scitotenv.2018.10.218

[7] Tian, S., Xu, M., Jiang, E., Wang, G., Hu, H. and Liu, X. (2019) Temporal Variations of Runoffs and Sediment Load in the Upper Yellow River, China. *Journal of Hydrology*, **568**, 46-56. https://doi.org/10.1016/j.jhydrol.2018.10.033

[8] Masayi, N.N., Omondi, P. and Tsingalia, M. (2021) Assessment of Land Use and Land Cover Changes in Kenya's Mt. Elgon Forest Ecosystem. *African Journal of Ecology*, **59**, 988-1003.

[9] Ndungo, M.J. (2021) Assessing Land Use-Land Cover Changes and Their Effects on the Hydrological Responses within the Nyangores River Catchment, Kenya. University of Western Cape, Cape Town, 199 p. http://etd.uwc.ac.za/

[10] Biervliet, O., Wiśniewski, K., Daniels, J. and Vonesh, J.R. (2009) Effects of Tea Plantations on Stream Invertebrates in a Global Biodiversity Hotspot in Africa. *Tropical Biology and Conservation*, **41**, 469-475. https://doi.org/10.1111/j.1744-7429.2009.00504.x

[11] Gebrejewergs, A., Atinkut, M. and Atkilt, G. (2020) The Effects of the Land Use Land Cover Change on Hydrological Flow in the Giba Catchment, Tigray, Ethiopia.

Cogent Environmental Science, **6**, Article ID: 1785780
https://doi.org/10.1080/23311843.2020.1785780

[12] Kundu, P. and Olang, L.O. (2011) The Impacts of Land Use Change on Runoff and Peak Flood Discharge for Nyando River in Lake Victoria Drainage Basin Kenya. *Ecology and the Environment*, **153**, 83-94.
https://doi.org/10.2495/WS110081

[13] Omengo, F., Geeraert, N., Bouillon, S. and Govers, G. (2016) Sediment Deposition Patterns in a Tropical Floodplain, Tana River, Kenya. *Catena*, **143**, 57-69.
https://doi.org/10.1016/j.catena.2016.03.024

[14] Gathagu, J.N., Sang, J.K. and Maina, C.W. (2017) Modelling the Impacts of Structural Conservation Measures on Sediment and Water Yield in Thika-Chania Catchment, Kenya. *Journal of International Soil and Water Conservation Research*, **6**, 165-174. https://doi.org/10.1016/j.iswcr.2017.12.007

[15] Mekuriaw, T. (2019) Evaluating Impact of Land-Use/Land-Cover Change on Surface Runoff Using Arc SWAT Model in Sore and Geba Watershed, Ethiopia. *Journal of Environment and Earth Science*, **9**, 7-17.

[16] Ochieng, W., Oludhe, C. and Dulo, S. (2019) Sustainable and Appropriate Climate Change Adaptation Strategies for Hydropower Developments in the Sondu Miriu River Basin. *International Journal of Scientific and Research Publications*, **9**, 218-224.
https://doi.org/10.29322/IJSRP.9.03.2019.p8735

[17] Masese, F.O., Raburu, P.O., Mwasi, B.N. and Etiegni, L. (2012) Effects of Deforestation on Water Resources: Integrating Science and Community Perspectives in the Sondu-Miriu River Basin, Kenya. In: Oteng-Amoako, A.A., Ed., *New Advances and Contributions to Forestry Research*, IntechOpen, London.

[18] Kroese, J.S., Batista, P.V.G., Jacobs, S.R., Breuer, L., Quinton, J.N. and Rufino, M.C. (2020) Agricultural Land Is the Main Source of Stream Sediments after Conversion of an African Montane Forest. *Scientific Reports*, **10**, Article ID: 14827.
https://doi.org/10.1038/s41598-020-71924-9

[19] Weeser, B., Stenfert, K.J., Jacobs, S.R., Njue, N., Kemboi, Z., Ran, A., Rufino, M.C. and Breuer, L. (2018) Citizen Science Pioneers in Kenya—A Crowdsourced Approach for Hydrological Monitoring. *Science of The Total Environment*, **631-632**, 1590-1599. https://doi.org/10.1016/j.scitotenv.2018.03.130

[20] Mungai, N.W., Njue, A.M., Samuel, A.G, Said, V.A. and John, D.I. (2011) Periodic Flooding and Land Use Effects on Soil properties in Lake Victoria Basin. *African Journal of Agricultural Research*, **6**, 4613-4623.

[21] Perzyna, G. (2016) Field Manual Current Meter Stream Flow Measurements by Wading. ECOWAS Centre for Renewable Energy and Energy Efficiency, Australian Development Cooperation, 48 p.

[22] APHA (2005) Standard Methods for the Examination of Water and Wastewater Manual. 21st Edition, American Public Health Association, American Water Works Association and Water Environment Federation, Washington DC.

[23] Ouma, K.O., Mungai, N.W. and Kitaka, N. (2013) Temporal Variation from Surface Runoffs from Agricultural Land Use in Sondu River Basin. *Journal of Environmental and Earth Science*, **5**, 577-590. https://doi.org/10.19026/rjees.5.5688

[24] Dahmen, E.R. and Hall, J. (1990) Screening of Hydrological Data: Tests for Stationarity and Relative Consistency. International Institute for Land Reclamation and Improvement/ILRIW, Wageningen, 58 p.

[25] Du., C.-J., Iqbal, A. and Sun, D.-W. (2016) Quality Measurement of Cooked Meats. In: Sun, D.-W., Ed., *Computer Vision Technology for Food Quality Evaluation*,

Academic Press, Cambridge, 195-212.

[26] Kitheka, J.U., Kitheka, L.M. and Njogu, I.N. (2022) Suspended Sediment Transport in a Tropical River Basin Exhibiting Combination of Land Uses/Land Covers and Hydroclimatics Conditions: Case Study of Upper Athi Basin, Kenya. *Journal of Hydrology: Regional Studies*, **41**, Article ID: 101115. https://doi.org/10.1016/j.ejrh.2022.101115

[27] Njogu, I.N., Kitheka, J.U. and Otieno, H. (2018) Streamflow Variability and Sediment Yield in North West Tana River Basin, Kenya. *Hydrology: Current Research*, **9**, Article No. 305.

[28] Woldesenbet, T.A., Elagib, N.A., Ribbe, L. and Heinrich, J. (2018) Catchment Response to Climate and Land Use Changes in the Upper Blue Nile Sub-Basins, Ethiopia. *Science of The Total Environment*, **644**, 193-206. https://doi.org/10.1016/j.scitotenv.2018.06.198

[29] Choto, M. and Fetene, A. (2019) Impacts of Land Use/Land Cover Change on Stream Flow and Sediment Yield of Gojeb Watershed, Omo-Gibe Basin, Ethiopia. *Remote Sensing Applications: Society and Environment*, **14**, 84-99. https://doi.org/10.1016/j.rsase.2019.01.003

[30] Jaimes, N., Sendra, J., Delgado, M., Plata, R., Némiga, X. and Solís, L. (2012) Determination of Optimal Zones for Forest Plantations in the State of Mexico Using Multi-Criteria Spatial Analysis and GIS. *Journal of Geographic Information System*, **4**, 204-218. https://doi.org/10.4236/jgis.2012.43025

[31] Hannouche, A., Chebbo, G., Ruban, G., Tassin, B., Lemaire, B.J. and Joannis, C. (2011) Relationship between Turbidity and Total Suspended Solids Concentration within a Combined Sewer System. *Water Science & Technology*, **64**, 2445-2452. https://doi.org/10.2166/wst.2011.779

[32] Tahiru, A., Doke, D. and Baatuuwie, B. (2020) Effect of Land Use and Land Cover Changes on Water Quality in the Nawuni Catchment of the White Volta Basin, Northern Region, Ghana. *Applied Water Science*, **10**, Article No. 198. https://doi.org/10.1007/s13201-020-01272-6

[33] Njue, N., Gräf, J., Weeser, B., Rufino, M.C., Breuer, L. and Jacobs, S.R. (2021) Monitoring of Suspended Sediments in a Tropical Forested Landscape with Citizen Science. *Frontiers in Water*, **3**, Article 656770. https://doi.org/10.3389/frwa.2021.656770

[34] Woldeab, B., Ambelu, A., Mereta, S. and Beyene, A. (2018) Effect of Watershed Land Use on Tributaries' Water Quality in the East African Highland. *Environmental Monitoring and Assessment*, **191**, Article No. 36. https://doi.org/10.1007/s10661-018-7176-3

[35] Nyangaga, J.M. (2008) The Effects of Enviromental Degradation on streAm Flow. Volume and Turbidity in the Itaresubcatchment within the Lake Victoria Drainage Basin, in Kenya. University of Nairobi, Nairobi, 113 p. http://erepository.uonbi.ac.ke:8080/xmlui/handle/123456789/21121

[36] Geeraert, N., Omengo, F.O., Tamooh, F., Paron, P., Bouillon, S. and Covers, G. (2015) Sediment Yield of the Lower Tana River, Kenya Is Sensitive to Dam Construction: Sediment Mobilisation Process in a Semi-Arid Tropical River System. *Earth Surface Processes and Landforms*, **40**, 1827-1838.

[37] Mello, K., Valente, R.A., Randhir, T.O., Santos A.A. and Vettorazzi, C.A. (2018) Effects of Land Use and Land Cover on Water Quality of Low Order Streams in Southeastern Brazil: Watershed versus Riparian Zone. *CATENA*, **167**, 130-138. https://doi.org/10.1016/j.catena.2018.04.027