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Stream Flow Variability and Sediment Yield in North-West Upper Tana Basin, Kenya

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Abstract

The North-West Upper Tana River (NWUT) Basin is one of Kenya's most important basins as it provides water for urban-rural water supplies, hydro-electric power (HEP) generation and irrigation. This study therefore investigated the influence of rainfall variability on the river discharge and sediment yield in the basin. The study relied on data archived by Water Resources Authority (WRA) and Kenya Meteorological Department (KMD) for the period 2010-2012. The methods applied in the study included the use of time series, double mass curve and the use of other statistical methods. The study established that there is a significant relationship between river discharge and rainfall in the basin. The variations in stream flow can largely be explained by variations in rainfall in the basin. There is however evidence of shift in rainfall patterns so that rainfall during the short rainy season seems to be more dominant than that experienced during the long rainy season. There is also a significant relationship between sediment yield and stream flow. The basin generally experiences high rates of sediment production due to inappropriate land use practices and lack of application of soil and water conservation measures on cultivated lands. Mathioya, Saba Saba, Thika and Maragua sub-basins exhibited high rates of sediment production rates due to high rates of soil erosion in these sub-basins. The high sediment yield in the basin has potential of reducing the benefits associated with Masinga Dam in terms of water supply, irrigation, flood control and HEP generation. The study recommends implementation of enhanced programmed for land and water conservation in the basin, including implementation of payment for Ecosystem Services (PES).

Keywords: North West Upper Tana; Sediment yield; Sediment production; River discharge

Introduction

Tana river in Kenya provides an important link between the Central Kenya Highlands and the Indian Ocean. This is in terms of freshwater, nutrients and sediment discharge. Through the discharge of various materials, the river plays as key role in supporting diverse marine and aquatic ecosytems in the Ungwana Bay part of the West Indian Ocean. However, various developments in the upper parts of the Tana Basin, particularly the Upper Tana Basin has led to major changes in material transport to the coast [1]. Past studies conducted in the basin have shown that Masinga reservoir-the largest reservoir in the basin and in Kenya, has significantly modified the flow of the Tana [2,3]. There has also been reduction of the sediment load of the river due to trapping of terrigenous sediments in the reservoir [1,3]. The siltation of the Masinga reservoir is progressively leading to the reduction of the storage capacity and the life expectacy of the dam [4-6]. Some studies have estimated that Masinga reservoir has already lost approximately 13.6% of its design storage capacity [7]. Without implementation of comprehensive soil and water conservation, including reduction in population in the Upper Tana Basin, storage capacity of Kenya's most important HEP reservoir would be reduced considerably before 2050 [7-10]. This will mean that the benefits associated with the dam such as the provision of water, hydropower generation, flood control, recreation including also ecological and environmental benefits will be signficantly affected [7].

In addition to the impacts of hydro-electric dams, climate change in the Upper Tana Basin is also significantly exerting changes in the flow of the river. In the recent past, there has been increased variability of rainfall in the Central Kenya Highlands-the main water catchment area for the Tana river. Changes in rainfall patterns have led to changes in streamflow (reduction) and sediment production (increase) at catchment level [4,11-14]. The impacts of climate change have been exercabated by landuse and landcover change in the basin. Since the beginning of the nineteeth century when the Central Kenya Highlands were opened for settlements and agriculture by the European settlers, there have been significant landuse and landcover changes that have led to high rates of soil erosion [2,4,13,15]. The extent to which these changes have impacted on the streamflow and sediment load of the river has however not been fully established due to lack of data. Several studies that have been carried out on river discharge and sediment yield in theUpper Tana catchment have not determined how key parameters such as rainfall variability and land use change overtime affects sediment yield and river discharge in the catchment [9,16,17]. Although the main variables impacting on streamflow and sediment yield are known to be land use, vegetation cover and rainfall variability, there is paucity of data to establish the interrelationship between these variables in tropical river basins of Africa. The influences of rainfall on streamflow and sediment yield are usually complicated by seasonal and inter-annual changes in land use and vegetation cover [13,15,18,19]. Therefore, without data on the seasonal and inter-annual changes in streamflow as well as land use/land cover changes, it becomes difficult to establish how the later is contributing to the current streamflow patterns in the Upper Tana Basin.

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The main objective of the study was to determine how streamflow and sediment yield are influenced by land use/landcover change and rainfall variability in the North-West Upper Tana catchment in Central Kenya. This study contributes to the current debate on the extent to which climate change and landcover/land use change influences river discharge and sediment yield in tropical river basins of Africa. The results obtained from this study will be invaluable in the formulation of appropriate and sustainable land and waters management strategies in the basin and elsewhere in Africa.

Description of the study area

North-West Upper Tana catchment is located in Central region of Kenya (Figure 1). The basin extends into Nyeri, Murang'a and Kiambu Counties. The study area is located between longitudes 36°30'0''E and 37°40'0''E and latitudes 1°10'0''S and 0°10'0''S (Figure 1). The basin covers a surface area of approximately 9,918 km^2 with elevation ranging from 881 m to 3,844 m above sea level [20]. The main river tributaries in the basin are Sagana, Mathioya, Maragua and Saba Saba, all of which feeds into the river Tana [21]. The basin is therefore the source of Kenya's largest and most important river system - Tana, which is used by Kenya Energy Generation Company (KenGen) to generate hydroelectricity power (HEP).

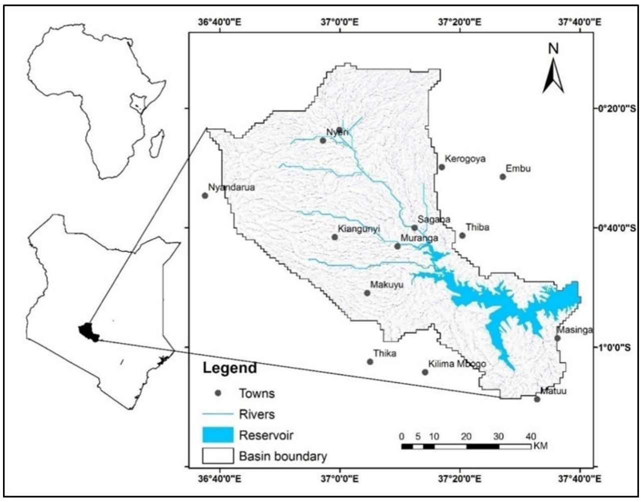

Figure 1: The location of North-West Upper Tana basin in Kenya (Njogu et al.).

Five major HEP dams that have been constructed in the lower reaches of the Upper Tana basin are Masinga, Kindaruma, Kamburu, Gitaru and Kiambere. Together, these dams provide approximately three quarters of electricity in Kenya and regulate the flow of the river Tana [7]. The basin experiences bimodal rainfall pattern due to the inter-tropical convergence zone (ITCZ). The long rain season is from March to May while the short rain season is from September to December [22]. The mean annual rainfall is of the order of 1,000 mm per annum but there are significant seasonal and inter-annual variations in rainfall. The maximum temperature ranging between 25-28ºC are experienced in the period between September and May while the coolest months are June-July-August when the average temperature is often less than 20°C. The basin is characterized by high population densities and extensive cultivation on steep slopes (Figure 2).

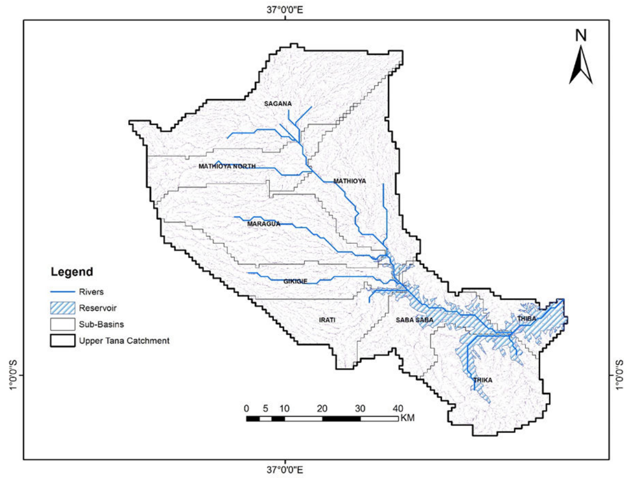

Figure 2: The main sub-basins in the North West Upper Tana basin.

Methodology

River gauging stations and stream flow data

This study relied on rainfall, river discharge and total suspended sediment concentrations (TSSC) data archived by Water Resources Authority (WRA) which is key government institution in Kenya responsible for collection of hydrological data. Stream flow data was obtained from WRA for nine (9) River Gauging Stations (RGS), namely Sagana (RGS 4AC03), Maragua (RGS 4BE01), Saba Saba (RGS 4BF01), Mathioya (RGS 4BD01), North Mathioya (RGS 4BD07), Irati (RGS 4BE03), Thiba (RGS 4DD01), Thika (RGS 4CC05) and Gikigie (RGS 4BE08). The archived river discharge data were mainly daily and monthly river discharges expressed in cumecs (m^3/s). These were subjected to time series analysis to determine seasonal and inter-annual variability in river discharge.

Rainfall data

Rainfall data used in this study was obtained from Kenya Meteorological Department (KMD) Head Office in Nairobi. Archived rainfall data was collected for key stations in the basin, namely Kiritiri Chief's camp, Nyeri Ministry of Works, Nyeri Meteorological Station and Sagana Fish Farm (see also Kerandi et. al., 2017). Sagana Fish Farm Station and Nyeri Ministry of Works rainfall stations had more consistent and long-term data as compared to other stations [23]. The study therefore relied on these two stations to infer on the long-term trends in rainfall.

Total suspended sediment concentrations data

The Total Suspended Sediment Concentrations (TSSC) data were obtained from Water Resources Authority (WRA) for the following River Gauging Stations (RGS): Sagana (RGS 4AC03), Maragua (RGS 4BE01), Saba Saba (RGS 4BF01), Mathioya (RGS 4BD01), North Mathioya (RGS 4BD07), Irati (RGS 4BE03), Thiba (RGS 4DD01), Thika (RGS 4CC05) and Gikigie (RGS 4BE08). TSSC data was also obtained from published sources [24].

Analysis of hydrologic data

The methods of analysis of hydrological data that were used in this study included Time-series analysis and Double Mass Curve analysis (DMCA). The time series analysis was used to show the seasonal and inter-annual trends on river discharge, sediment yield and Total Suspended Sediment Concentration (TSSC) for the period between 2010 and 2012. Double mass curve was used to check the consistency in rainfall, streamflow and sediment data, including the relationship between rainfall and river discharges [25]. This involved comparison of data from one gauging station which shows considerable consistency with another set of data from different gauging stations in the surrounding area [26]. Breaks on the double mass curve are caused by changes in relationship between variables under examination [27].

Computation of suspended sediment load

The total Suspended Sediment Load was computed using equation 1 by multiplying the instantaneous Total Suspended Sediment Concentration (TSSC) data with the instanteneous river discharge (Q) data according to equation 1 shown below [28,29].

$$Q_L = \sum_n^{i=1} Q_i . C_i \qquad (Eq.1)$$

Where Q_L is the Total Sediment load (tons/month), Q_i is the monthly instantaneous river discharge (m^3/month), and $C_i$is the monthly TSSC (kg/m^3). Computations on the total Suspended Sediment Load were done for Sagana River Gauging Station (RGS 4AC03), which forms the outlets from the basin to the main river Tana. The basin Sediment Production Rate was computed using equation 2 shown below.

$$(SRP) = \sum_n^{i=1} \frac{QL}{A} \qquad (Eq.2)$$

In equation 2 above, A is the basin area (km^2), Q_L is the instantaneous monthly sediment load (tonnes/month) and Q_i is the instantaneous river discharge (m^3/month).

Statistical methods of data analysis

The statistical methods of data analysis that were used for this study were measures of central tendency, measures of dispersion, regression analysis, correlation analysis and analysis of variance.

Results

Inter-seasonal and inter-annual variation of stream flow

There is a significant inter-seasonal and inter-annual variation in streamflow in North-West Upper Tana Basin. These variations are related mainly to variations in climatic conditions particularly rainfall in the basin. Figure 3 shows variation in streamflow for the period between July 2010 and May 2012. There is a significant difference between flows that were measured in the year 2010 and those that were measured in 2011 and 2012. The year 2010 experienced relatively higher streamflows for all the rivers found in the NWTB with river discharge reaching 170 m^3/s for the main Sagana river. The flows were generally higher in the period between September and December 2010 and 2011. On the other hand, the stream flows were low in the period between January and August 2011.

As can be observed in Figure 3, the streamflows were generally higher during the short rainy seasons in both years. There is evidence of extension of the short rainy season with the streamflows beginning to rise much earlier than the usual period of commencement of short rains in October. Data shows the streamflows increasing rapidly from the month of August to attain the peak in October. From the month of October, there is a rapid decline in streamflow up to February-March period. It is important to note that during the long rainy season, the streamflows were unusually low. During this period, river discharges in most of the rivers were of the order 0.10-0.19 m^3/s. Saba Saba river (RGS 4BF01), Mathioya river (RGS 4BD01) and Gikigie river (RGS 4BE08) in particular, experienced the minimal flows during the long rainy season.

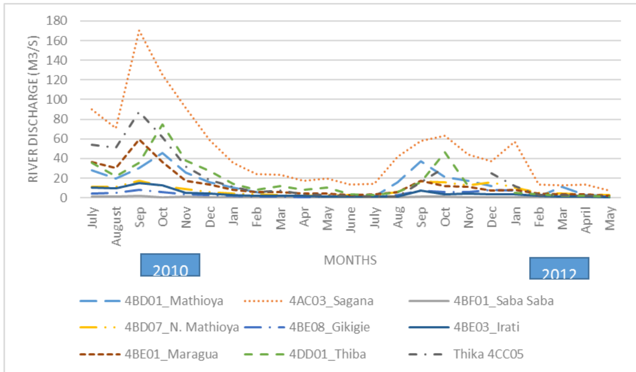

Figure 3: The variability in river discharge (m^3/s) for various rivers in the NWTB in the period between July 2010 and May 2012 [31].

It is important to note that the results presented in Figure 3 shows significant shifts in the patterns of streamflow in the North-West Upper Tana Basin. These shifts can be attributed to climate change that is probably leading to significantly low rainfall during the traditional long rainy season. It seems that relatively higher rainfall now occurs during the traditional short rainy season. Even then, the short rainy season seems to be beginning much earlier (in August-September) than in the past when the month of the normal commencement of short rains was October. The short rainy season seems to extent up to the months of February and March in the basin. It is also clear from Figure 3 that the traditional long rainy season (March-April-May) seems to be losing its dominance and short rainy season (October-November-December) seems to be becoming more dominant season in the basin (Figures 3 and 4).

The statistical analysis of the relationship between rainfall and river discharge, showed that there is indeed a significant relationship between streamflow and rainfall in NWUT basin. The correlation coefficient (r) and coefficient of determination (R^2) were 0.81 and 0.65, respectively. These results shows that about 65% of the variability of streamflow in the basin can be explained by variations of rainfall. The other 35% of the variations can perhaps be attributed to basin factors including water abstraction, landcover/landuse, depression storage, among other factors, that were subject of investigation in this study.

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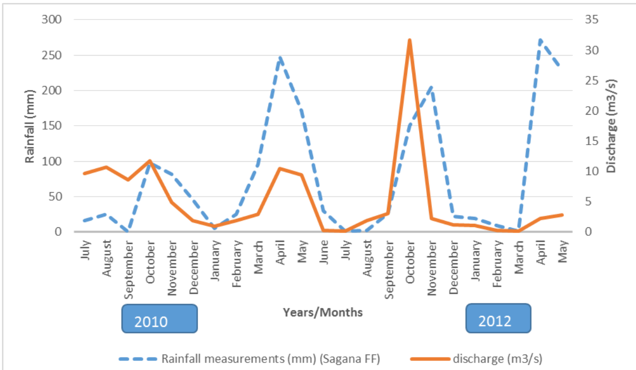

Figure 4: Relationship between rainfall (mm) and streamflow (m^3/s) in the period of July to May (2010-2012) [31].

Spatial temporal variability in river discharge

Stream flow of rivers found in the North-West Upper Tana shows significant differences and no two rivers have the same level of discharges. Rivers that experienced relatively higher streamflows are Sagana, Thiba, Thika, North Mathioya and Mathioya, where the river discharges reached a maximum of 170 m^3/s. Within a given river system in the NWUT Basin, there are also significant changes in the maximum river discharges from one season to the other and from one year to the other. For instance, streamflow at Sagana river (RGS 4AC03) attained the maximum values of 170 m^3/s in the period between 2010 and 2012. For Mathioya river (RGS 4BD01), the dry season river discharge ranged from 36 to 57 m^3/s. The maximum river discharges for the river ranged from 12 to 46 m^3/s. The typical flows during the rainy season for Mathioya river ranged from 37 to 46 m^3/s, and the typical dry season flows were of the order of 10 m^3/s.

The maximum river discharges for Maragua River (RGS 4BE01) was 59 m^3/s during the period of this study. The river discharge ranged from 17 to 59 m^3/s during rainy season and during the dry season, the flow was nearly constant being of the order 8 m^3/s. The maximum river discharge for Thika river (RGS 4CC05) was 87 m^3/s and the higher flows for this river generally ranged from 11 m^3/s to 87 m^3/s during rainy seasons. The maximum river discharges for Thiba river (RGS 4DD01) was of the order 74 m^3/s. The dry seasons flow for the river was of the order 5 m^3/s.

Significantly low river discharges in the North West Upper Tana basin were observed in Irati, Gikigie, North Mathioya and Saba Saba rivers where the flows were generally low. For instance, the river discharge for Saba Saba river (RGS 4BF01) attained the highest river discharge ranging from 0.27 to of 2.1 m^3/s during the rainy seasons. The results presented in preceding sections shows evidence of significant interseasonal variations in both the maximum and minimum streamflows in the basin. While rainfall is considered to be a key factor influencing streamflow variability, other factors such as land use/land cover change and water abstraction seems to be important.

Double mass curve analysis was used to check the consistency of the river discharge data obtained from the Water Resources Authority (WRA). The cumulated river discharge for Sagana river (RGS 4AC03) was plotted against the cumulated monthly average from other stations in the study area. The double mass curve presented in Figure 5 yielded a coefficient of determination (R^2) of 0.99 and correlation coefficient of (r) of 0.99, which generally shows a strong relationship. This means that the river discharge data was consistent from all the stations during the period of this study (Table 1).

Sub-Basin	Maximum River Discharge (m^3/s)	Minimum River Discharge (m^3/s)	Mean River Discharge (m^3/s)
Sagana	170.4	7.4	47.9
Mathioya	45.8	0.4	13.8
N. Mathioya	17.6	2.23	7.8
Maragua	59.4	2.3	13.1
Irati	14.9	0.8	4.2
Gikigie	7.9	0.8	3.5
Saba Saba	2.1	0.1	0.6
Thiba	74.4	1.2	17.5
Thika	87.4	0.9	19.6

Table 1: The range of some of the key river discharge parameters in the basin.

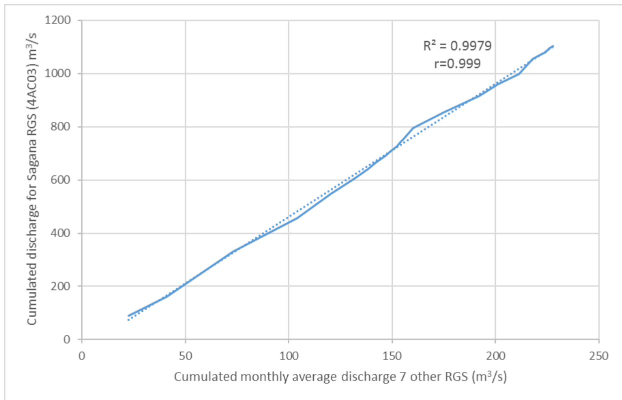

Figure 5: Double Mass Curve for the cumulated river discharge from Sagana river and other rivers in the North-West Upper Tana basin [31].

Variation of sediment concentrations

The rivers draining the NWUT basin show great variability in Total Suspended Sediment Concentration (TSSC). The TSSC data obtained for the period between 2010 to 2012 showed significant spatial temporal variability in suspended sediment concentrations (Figure 6). The highest values for Total Suspended Sediment Concentration (TSSC) ranging from 800 to 1,400 mg/l, were recorded in the Saba Saba river (RGS 4BF01) during the short rain's seasons. The maximum TSSC for the Thika River (RGS 4CC05) was of the order 120 mg/l. The maximum TSSC for Gikigie River (RGS 4BE08) and North Mathioya river (RGS 4BD07) were the lowest in the NWUTB as TSSC ranged from 19 to 514 mg/l during rainy season and was of the order of 5 mg/l during the dry season. High TSSC are normally associated with high rates of soil erosion and therefore it can be deduced from these data that the highest rates of soil erosion occur in the Saba Saba, Maragua and Mathioya sub basins of the NWUTB. These are areas contributing most of the sediments to the Sagana river which subsequently flows into the Tana river. Therefore, soil and water conservation programmes need to be enhanced in these sub-basins (Table 2).

Sub-Basin	Maximum TSSC (mg/l)	Minimum TSSC (mg/l)	Mean TSSC (mg/l)
Sagana	500	3	56.6
Mathioya	258	3	42.8
N. Mathioya	27	4	9.1
Maragua	517	3	65.1
Irati	67	2	15.9
Gikigie	19	4	8
Saba Saba	1433	10	242.6
Thiba	107	5	29.4
Thika	152	3	43.6

Table 2: The range of some of the key sediment parameters in the basin.

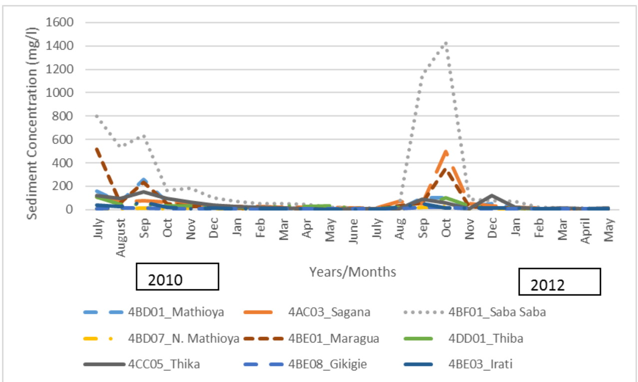

Figure 6: The variability of the Total Suspended Sediment Concentration (TSSC) (mg/l) in the North West Upper Tana Basin in the period between 2010 and 2012 [31].

Variation of sediment yields

Sediment yield in rivers draining the NWUT shows significant seasonal variation. Figure 7 shows variations in sediment yield in the period between 2010 and 2012. As expected, the highest levels of sediment yield occurred during the short rains season and the values were generally lower during the long rains season. It must be recalled that it is during the short rains season that the NWUTB experienced maximum rainfall and by extension, maximum surface runoff and subsequently maximum river discharges. The highest rates of sediment yield at Sagana river (RGS 4AC03) which receives contributions from other rivers, was 82,000 tons/month during rainy season. Maragua river (RGS 4BE01) also had relatively high sediment yield of the order of 48,000 tons/month the sediment yields were generally low during the dry seasons when river discharges were generally low. During these periods of relatively low streamflows, the sediment yield in the Sagana river was of the order 2,500 tons/month.

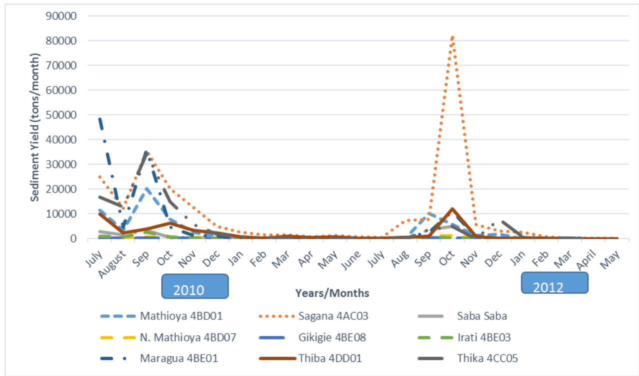

Figure 7: The variability in Sediment Yield (tons/month) in the main sub-basins in NWUTB in the period between July 2010 and May 2012 [31].

The rivers that recorded relatively high sediment yields during the period of the study were Sagana, Maragua, Mathioya and Thika rivers. These rivers had sediment yield ranging from 48,000 to 82,000 tonnes per month. On the other hand, rivers that recorded the lowest sediment yields were North Mathioya, Irati and Gikigie. These rivers had relatively low sediment yields ranging from 290 to 350 tonnes per month during short rainy season. During dry seasons when the river discharges for these rivers were low, the sediment yield ranged from 23 to 155 tons/month. The sub-basins with the highest sediment yield are those that experiences high rates of soil erosion that can be attributed to land cover/land use change, inappropriate farming practices and cultivation of steep slopes without application of soil conservation measures. Low sediment yields were generally in the small sub-basins draining the well vegetated slopes of the Aberdare ranges where land use include tea plantations that offers significant protection to the soil against erosion by water.

Influence of rainfall and stream flow on sediment yield

There is a significant relationship between rainfall and sediment yield in the North-West Upper Tana catchments (Figure 8). The increase in rainfall causes a corresponding increase in sediment yield. For instance, the peak sediment yield of 82,166.4 tons/month in the Sagana river was recorded when monthly rainfall was 150 mm. During the short rainy season, the sediment yield attained a maximum at the beginning of rainy season when the vegetation cover was low such that it could offer maximum protection against soil erosion. However, this was not the case during the long rainy season as the period of maximum sediment yield corresponded to the period of maximum rainfall. In general, sediment yield decreased as the rainy season progressed because of improved vegetation cover that intercepts rainfall and dissipates surface runoff and protects soil against detachment. During dry seasons when streamflows were low, sediment yield was also low. The relationship between rainfall and sediment yield had a correlation coefficient (r) of 0.87 and coefficient of determination (R^2) of 0.75, both of which were statistically significant (p=0.05). These results show that rainfall variations explain 75% of the variations in sediment yield in NWUT basin.

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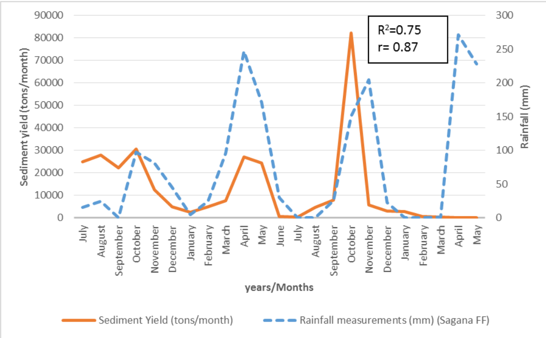

Figure 8: Relationship between rainfall (mm) and Sediment yield (tons/month) in the North-West Upper Tana catchment in the period between 2010 and 2012 [31].

There is significant relationship between TSSC and streamflow for rivers draining the NWUT basin (Figure 9). The relationship between the two parameters yielded a correlation coefficient (r) of 0.74 and a coefficient of determination (R^2) of 0.59. Thus, while there is a significant relationship, streamflow can only explain 59% of the variations of TSSC. The best relationship between the two parameters was represented by the power function equation shown in Figure 9. The results showed that TSSC increases as the river discharge increases. This is expected since the sediment transport capacity of the rivers increases as the river discharge increases [10,27]. At high flows, the rivers are able to carry more volume of sediments, although the suspended sediment concentrations can be relatively low. We have however to be cautious of the fact that most of the TSSC measurements were undertaken when streamflows were less than 90 m^3/s. The TSSCs were relatively higher for low streamflow conditions as compared to high streamflow conditions.

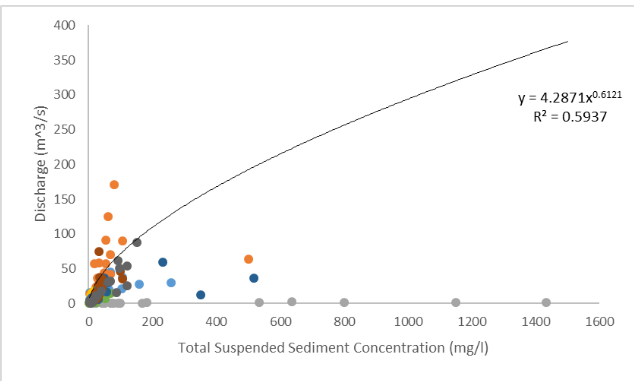

Figure 9: The relationship between river discharge (m^3/s) and Total Suspended Sediment Concentration (TSSC) (mg/l) in the NWUTB in the period of July 2010 to May 2012 [31].

The study also established that there is also significant relationship between streamflow and sediment yield as shown in Figure 10. The sediment yield increases as streamflow increases because at high streamflows, rivers have greater capacity to transport suspended sediments. The relationship was best presented by a power function as opposed to linear function. Consequently, the highest sediment yield of the order of 35,000 tons/month occurred during high streamflow of 170 m^3/s. The lowest sediment yield of the order of 3 tons/month occurred during low flows of 0.12 m^3/s. The relationships were confirmed through computation of the correlation coefficient (r) and coefficient of determination (R^2) which were 0.98 and 0.96, respectively. As expected, these results show that variations in streamflow explains 96% of the variations in sediment yield.

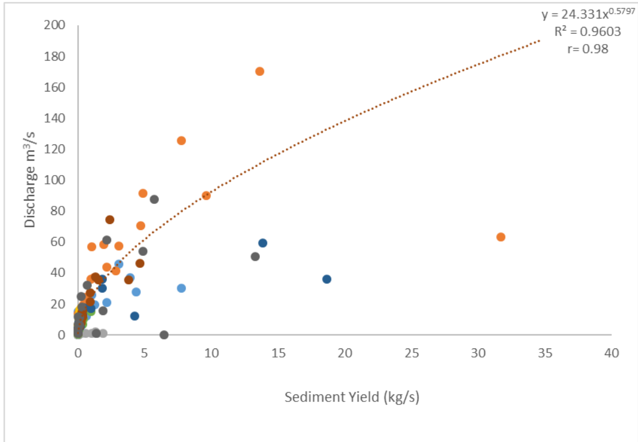

Figure 10: Relationship between river discharge (m^3/s) and sediment yield (kg/s) in the NWUTB in the period of July 2010 to May 2012 [31].

Water yield and sediment production rates in the sub-basins

Sediment production rates in each of the sub-basins draining the Northwest Upper Tana basin were computed by diving the sub-basin sediment yields by the corresponding sub-basin areas. Results shown in Table 3 provides an insight on sub-basins with relatively high sediment production rates which basically are related to high soil erosion rates. Sagana river basically obtains contributions from other rivers listed in Table 3 with the exception of Thika and Thiba rivers. Therefore sediment production rate at river Sagana is representative of the entire NWUTB while the rest represents sediment production rates at sub-basin level. From these results, it can be observed that sediment production rate in the NWUTB is of the order 152 $tons/km^2/month$ while the water yield is 124 × 10^6 m^3 per month. The sub-basins with the highest sediment production rates (and hence high soil erosion rates) are Maragua, Mathioya, Thika and Thiba. The sub-basins with the lowest sediment production rates are Irati, Gikiye, Saba Saba and North Mathioya. These are sub-basins located in the upper zones of NWUTB which has relatively better vegetation cover. The sub-basins with high sediment production rates are characterized by intensive cultivation on steep slopes with little application of soil conservation measures. These sub-basins are also relatively densely populated with many footpaths and murram rural roads that are sources of sediments that ends up in the river systems. In this respect, soil and water conservation measures need to be enhanced in Maragua, Mathioya, Thika and Thiba sub-basins in the NWUTB. This will result in considerable benefits in terms of reduction of sediment load of river Tana and this will subsequently reduce sedimentation in the Seven Folk Dams including other smaller dams constructed in the basin.

Sub-basin	Water Yield (m^3/month)	Sediment Yield (tons/month)	Sub-basin area (km^2)	Sediment production rate (tons/km^2/month)
Sagana (4AC03)	124,262,734	228,702.6	1,501.26	152.34
Mathioya (4BD01)	35,253,454	65,881.49	1,318.32	49.97
N.Mathioya (4BD07)	20,342,692	5,444.055	957.58	5.69
Maragua (4BE01)	33,998,024	112,241.1	1,307.21	85.86
Irati (4BE03)	10,965,287	7,035.388	889.19	7.91
Gikigie (4BE08)	9,174,553	2,166.186	1,021.69	2.12
Saba Saba (4BF01)	1,578,866	17,742.11	1,011.43	17.54
Thika (4CC05)	48,654,094	104,914.1	1,186.68	88.41
Thiba (4DD01)	43,427,270	46,510.41	725.06	64.15
Total for NWUT basin	327,638,974	590,637.4	9,918.42	59.55

Table 3: Water yield, sediment yield and sediment production rates in NWUT basin [31].

Discussion

The results of this study show that rainfall variation is the driver of the variations in streamflow in sub-basins found in the NWUT basin in Central Kenya Highlands. The variations in rainfall explains 65% of the variations in streamflow indicating that other factors also influence streamflow in the basin. These factors could include water abstraction and water diversion which in the recent past have become a matter of concern to the Water Resources Authority (WRA). Therefore, it can be argued that changes in rainfall in the basin as a result of climate change would significantly affect stream lows and the problem would be compounded by increasing water abstractions and diversion of river flows. Also, the effect of land cover change may be contributing to the observed variations in streamflow.

The effect of climate change is already notable in the data that were obtained from WRA. As was shown in Figure 3, there is clear evidence of significant shifts in the patterns of streamflow in the Northwest Upper Tana Basin, with relatively higher flows occurring during the short rainy season as compared to the long rainy season. It seems that more rainfall occurs during the short rainy season as compared to the long rainy season and this seems to be a new trend. These shifts can be attributed to climate change, although there is no certainty on the same due to lack of good long-term data on rainfall and streamflow.

However, available data shows that the short rainy season is now commencing much earlier (in August-September) than in the past when the season used to begin from the month of October. In fact, data shows the short rainy season to be extending up to the months of February and March which in the past used to be predominantly dry periods in the basin. It is also clear from the data that the traditional long rainy season (March-April-May) seems to be becoming less dominance as compared to the short rainy season (October-November-December). Perhaps this explains why some of the dams located in the basin (e.g., Ndakaini dam) did not fill up with water during the long rainy season of 2018, despite floods that were experienced in other parts of the country [30].

The results of the study also showed that some sub-basins within the NWUT Basin experiences high rates of soil erosion. These sub-basins include Saba Saba, Maragua and Mathioya sub-basins. In these sub-basins, the TSSC values were generally higher implying high rates of soil erosion. These sub-basins had sediment yield ranging from 48,000 to 82,000 tonnes per month. This was attributed to high rates of soil erosion that are due to inappropriate landuse practices since these sub-basins are generally heavily cultivated with high population densities. On other hand, the sub-basins draining the well vegetated slopes of the Aberdare mountain ranges such as Gikigie, Irati and North Mathioya exhibited low levels of TSSC, indicating these sub-basins experiences low soil erosion rates. These basins are therefore characterized by relatively low sediment yields at their outlets ranging from 290 to 350 tonnes per month during short rainy season. During dry seasons when the river discharges for these sub-basins were low, the sediment yield ranged from 23 to 155 tons/month. The results indicate Saba Saba, Maragua and Mathioya rivers contributes most of the sediments to the Sagana river which subsequently flows into the river Tana. Therefore, soil and water conservation programmes need to be enhanced in these sub-basins to protect cultivated land against soil erosion. This is a major challenge given high population densities, small sized land parcels and major investments required in the implementation of comprehensive soil conservation and re-afforestation programmes. In addition, given that substantial quantity of sediments originates from numerous footpaths and earth/murram rural roads, it is unlikely that the application of soil conservation measures such as contours and terraces alone would lead to a major reduction in the volume of sediments that is carried by surface runoff into the rivers. Effort would need also need to focus on improving rural roads and footpaths.

The results of this study showed that an increase in rainfall causes a corresponding increase in sediment yield in the sub-basins found in the NWUTB. It is evident from our results that during the short rainy season, the sediment yield attains a maximum at the beginning of rainy season when the vegetation cover was low and therefore cannot offer maximum protection against soil erosion. However, it was surprising to note that this was not the case during the long rainy season as the period of maximum sediment yield corresponded to the period of maximum rainfall. Thus, it seems that there is a difference in terms of the intensity of vegetation cover during the two seasons with relatively better cover during the periods preceding the long rainy season and perhaps significantly lower vegetation cover in the period preceding the short rainy seasons when most of the rainfall occurs. In general, it is normally expected that sediment yield would be highest at the beginning of the rainy season and there should be a progressive decline as vegetation cover improves in the basin during the latter part of the rainy season. Improved vegetation cover, which also includes cultivated crops on farms (tea, coffee, maize, beans) intercepts rainfall and dissipates surface runoff and protects soil against detachment. However, this is subject of further research, as the current data could not allow us to determine the extent to which progressive improvement in vegetation cover leads to changes in sediment production rates from cultivated and no-cultivated lands.

The Upper Tana Basin is the most important in the entire Tana River Basin and considerable effort has been directed towards the exploitation of water in the region. The results of this study show that North-West Upper Tana basin (NWUTB) is important in terms of water and sediment yield as the total river discharge is of the order 3.28 $\times 10^6$ m^3/month and the sediment yield is of the order of 590,637.4 tons/month. Through simple extrapolation, it can be deduced that the NWUTB water contribution to the greater river Tana is of the order of 39.4 $\times 10^6$ m^3 per year. Likewise, the sediment load contribution to the greater Tana river system is of the order of 7.1 $\times 10^6$tonnes per year with the sediment production rate being 59.6 tons/km^2/month which is approximately 715 tons/km^2/year from the basin. This can be said to be representative of the conditions during the period 2010-2012. The sediment load and sediment production rate per unit basin area are quite high and these are attributed to high rates of soil erosion in some of the sub-basins, particularly Maragua, Mathioya and Thika [17,31]. Previous studies have estimated the sediment load in the Upper Tana Basin to be in the range of between 0.88 $\times 10^6$ and 2.3 $\times 10^6$ tons/year [17]. Our data and those of previous studies would therefore put the sediment load in the Upper Tana Basin to be in the range of 0.88 $\times 10^6$ and 7.1 $\times 10^6$ tonnes per year [1,4]. This high sediment load has major implication on reservoirs constructed downstream of the Upper Tana Basin. Masinga Dam reservoir which is the main water storage reservoir for the Seven Folk HEP Dams is the most affected [32-34]. Although data on the sedimentation rates within Masinga dam are not currently available, it has been argued that high rates of sediment input into the reservoir is rapidly reducing the design capacity of the dam and this in the near future would make the dam less useful for water storage, water supply and flood control downstream [8,35]. This may necessitate commissioning of expensive dredging operations that will drain the meager financial resources of the Kenya Government. Thus, while there is increasing dependence on reservoirs in most tropical countries as part of strategies of coping with the impacts of climate change, inappropriate land use practices can drastically reduce the benefits that are accrued from the construction of dams [36]. Catchment degradation can reduce the benefits associated with heavy investments incurred in the construction of dams, particularly in African countries. There is therefore a need to enhance soil and water conservation measures in river basins targeted for construction of dams for provision of water for rural-urban water supply, irrigation, flood control and HEP generation. In addition to implementation of the traditional soil conservation strategies such as contouring and terracing, there is a need for better construction of rural roads and footpaths.

Conclusions

This study investigated streamflow variability and sediment yield in North-West Upper basin using data that were collected in the period between 2010 and 2012. Although the study was limited by the lack of long-term data, it was established that there is a significant relationship between streamflow and rainfall in the North-West Upper Tana basin. The variations in rainfall explains the streamflow variations in the basin. Therefore, changes in rainfall patterns as is already happening during this era of climate change, will induce corresponding changes in streamflow in the basin. There is an indication of significant shift in the occurrence of short rains and long rains season with the short rains becoming more dominant in terms of rainfall amounts and streamflow. However, this finding needs to be subjected to further studies using long-term data. The study also established that sediment yield and sediment production rates are a function of rainfall and streamflow, although land use/land cover also plays an important role. Some sub-basins in the Upper Tana Basin such as Mathioya, Saba Saba, Thika and Maragua are characterized by high sediment production rates which is an indication of high rates of soil erosion. There is therefore a need to enhance soil and water conservation in these sub-basins in order to reduce high rates of soil erosion. The high sediment production rates in the Northwest Upper Tana Basin have led to high sediment discharge into Masinga dam which is the most important dam in Kenya. Without change in landuse and without application of comprehensive soil conservation strategies, high sediment input into Masinga dam have potential of reducing its overall benefits in terms of provision of water for rural-urban water supply, irrigation, flood control and HEP generation. In view of the importance of the NWUT Basin to the greater Tana river system, this study recommends a comprehensive water and sediment quality monitoring programme to be implemented in the basin in order to collect long term data for research and water resources management in the basin. In addition, there is a need for implementation of Payment for Ecosystem Services (PES) in the basin so as to motivate farmers to implement soil and water conservation measures.

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