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A PROPOSED APPROACH OF SEDIMENT SOURCES AND EROSION PROCESSES IDENTIFICATION AT LARGE CATCHMENTS

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Abstract: In the subject of identifying sediment sources and erosion processes at catchment level researchers have proposed various methods. Most of the techniques have been applied in isolation. A few workers have combined some methods but still they could not ascertain their findings. As a result they recommended more sophisticated methods in order to compare the results. Little however has been done to correlate suspended sediment concentrations using spatial and temporal hydrological variables like rainfall and surface runoff at reasonable time step such as daily time series. In this study selected methods by previous workers are used and compared. The hydrological variables mapping technique has complemented the results of various renowned sediment sources identification techniques. The introduced method gives not only probable sources and processes but also it additionally identifies location based sediment sources using rainfall stations as pointers. The combined results from both methods indicate that either clay soil land plots or agricultural areas are potential sediment source areas. The result is comparable to previous researchers' findings in the Pangani River basin that mapped the erosion zones using simple empirical and complex physics-based mathematical models. Although, the methods adopted in this study lacked high-resolution data, the authors believe that the methods and modifications applied give a quick, reliable and more insight to future sediment yield modelling efforts at a catchment level. For instance, a distributed watershed sediment yield model would be appropriate based on high spatial and temporal variation of the hydrological variables as reported in this study. Also, the results suggest that Sediment yield model that simulates sheet erosion might be an ideal tool since the major source areas of the transported sediment are topsoils or sheet erosion.

Keywords: Correlation; erosion processes; fingerprint; hydrologic variables; sediment sources

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INTRODUCTION

An ideal way to study erosion sources and processes would be to collect the sediment flow data spatially, at least from each of the river tributaries. Such a research project would definitely be demanding in terms of resources (i.e. time, funding and personnel) and logistical issues (Ndomba, 2007).

A number of indirect methods for evaluating sediment sources exist. Basic relationships between concentration of suspended sediment (C) and water discharge (Q) during single hydrologic events have been used by others (Peart & Walling, 1988; Williams, 1989; Ndomba, 2007) as indirect method to identify sediment sources. However, the potential mix and interrelationships of these and other variables present a formidable challenge to predicting the type and magnitude of C - Q relation for a particular site and occasion (Williams, 1989). Because of the problems associated with sediment storage and evaluating erosion based on direct methods, Peart & Walling (1988) had difficulties in quantifying the contribution made by bank erosion. Besides, other researchers such as Bogen & Bønsnes (2003) have used suspended sediment concentration rating curves to analyze the processes. The application of such approach would be limited to catchments where no adverse changes in landuse/landcover or landscape modification have taken place (Ndomba, 2007). Another more elaborative indirect method applied by many workers is the fingerprinting technique to date. This method is based on the principal that sediments in suspension maintain some of the geochemical properties of their parent material, and that these properties can thus be used as tracers (Minella *et al.*, 2004). However, the use of sediment property data to evaluate sediment source is not without difficulties.

The foregoing discussions suggest that there are no compelling methods on this subject. Although precipitation intensity and areal distribution and runoff amount and rate are known hydrological variables that influence the sediment transport, to the knowledge of the authors little or none has been done to correlate these variables at reasonable time scale (daily and hourly) at a catchment level. Rainfall was conceived in this study as a trigger and driver of runoff and thus sediment.

Therefore, the study explores the spatially distributed nature of the rainfall stations in the catchment to correlate to sediment sources, locating site specific sediment sources. The authors of this paper believe that the approach indirectly imitates distributed modelling philosophy. Besides, temporal mapping of hydrological variables such as rainfall, total stream flow and surface runoff are used in this study to analyze the seasonal sediment fluxes responses, for erosion processes identification. The proposed method is validated using previous erosion study findings in the same catchment.

MATERIAL AND METHODS

The Pangani River Basin (PRB) is located, between Latitudes, 02°55’S and 05°40’S; Longitudes, 36°20’ E and 39°02’ E, in the North Eastern part of Tanzania and covers an area of about 42,200 km^2, with approximately 5% in Kenya (**Fig. 1**). The Pangani River has two main tributaries, the Kikuletwa (1DD1) and the Ruvu (1DC1) (**Fig. 1**), which join at Nyumba Ya Mungu (NYM) a reservoir of some 140 km^2.

The study area is the Nyumba Ya Mungu Reservoir (NYM) catchment located in the upstream of PBR (**Fig. 1**). The main subcatchments in the study area are Weruweru, Kikafu, Sanya, Upper Kikuletwa and Mount Meru slopes. The catchment of NYM occupies a total land and water area of about 12,000 km^2 (Ndomba, 2007) It is located between Latitudes 3°00'00" and 4°3'50" South, and Longitudes 36°20'00" and 38°00'00" East. This area has an average annual rainfall of about 1000 mm. The rainfall pattern is bimodal with two distinct rainy seasons, long rains from March to June and short rains from November to December (Rohr, 2003). Recent findings by Rohr and Killingtveit (2003) indicate that the maximum precipitation on the southern hillside of Mount Kilimanjaro takes place at about 2,200 m.a.s.l., which is 400–500 m higher than assumed previously. The altitude in the study area ranges between 700 and 5,825 m.a.s.l. with Mount Killimanjaro peak as the highest ground. Based on the Soil Atlas of Tanzania (Hathout, 1983), the main soil type in the upper PRB is clay with good drainage (**Fig. 1**). It should be noted that polygons mapped in **Fig. 1** represent soil type coverage. Actively induced vegetation, forest, bushland and thickets with some alpine desert chiefly characterize the land cover of the catchment.

This study used the technique of mapping of hydrological variables such as rainfall in spatial and temporal domain in relation to sediment transport characteristics at the outlet of the catchment. An Automatic pumping sampler, ISCO 6712, was used to collect high frequent subdaily sediment samples (i.e., between 2 and 12 samples a day) at 1DD1 gauging station (**Fig. 1**).

For the purpose of validating the proposed approach, this study adopted multi-approaches to identify the sediment sources and erosion processes. The known methods used in this study include analyses of single hydrological events as sampled from continuous sediment pumping sampler and water levels recording data logger; fingerprinting approach where organic matter contents and particle size distribution of the transported sediment by rivers or those deposited in the downstream reservoirs give clues on the origin and processes of sediment in the catchment. The details of which can be found in Ndomba (2007).

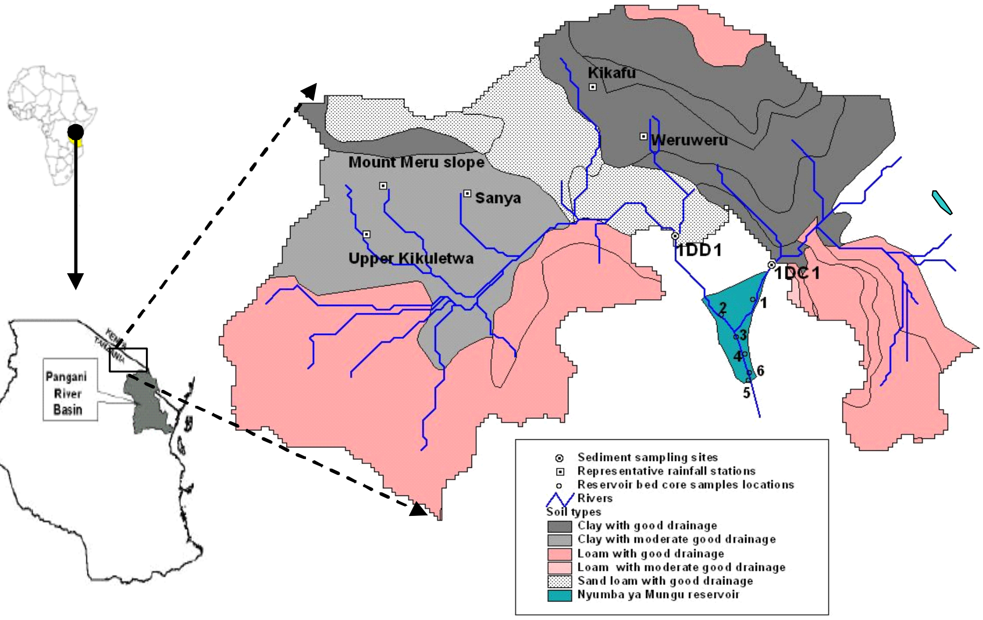

Fig. 1 A location map of Nyumba Ya Mungu Reservoir catchment and sediment sampling sites, in the study area.

RESULTS AND DISCUSSION

Spatial and temporal mapping of hydrological variables: rainfall, discharges and surface runoff

This analysis was conducted at a test sub-catchment called 1DD1 where adequate and reliable hydrological data is available (**Fig. 1**). Five representative rainfall stations out of 31 used in the analysis include Kibong'oto Hospital station (9337078); Masama Estate (9337028); Dolly Estate (9336015); Imani Estate Oljoro (9336059) and Themi Estate (9336013); located near the centroid of the main subcatchments called Kikafu, Weruweru, Sanya, Upper Kikuletwa and Mount Meru slopes subcatchments, respectively, were used (**Figs 1** and **2**, and **Table 1**).

The numbers in the brackets are the rainfall station codes. However, you will note that for clarity purpose not all rainfall stations were mapped in **Fig. 1**. The entire set of 31 rainfall stations as presented in **Table 1** above was used to fill missing data in representative stations with the help of Inverse distance square algorithm. An areal rainfall method was considered not suitable because many stations have missing data and its lumping nature in spatial domain would distort the rainfall intensity and sensitivity to flow discharges and sediment downstream at 1DD1 station.

The same data quality and set of rainfall stations was successfully used by Ndomba (2007) in sediment yield modeling work. The rainfall pattern in the catchment is known to be highly spatially variable (Rohr, 2003; Rohr & Killingtveit, 2003).

Table 1. Inventory of rainfall stations used in the study

Station code	Location			Data availability			
	Latitude	Longitude	Elevation (masl)	Start year	End year	Period (years)	Missing (%)
9336000	-3.30	36.65	1609	1928	1993	66	9
9336001	-3.38	36.68	1372	1922	1994	73	5
9336011	-3.35	36.60	1402	1927	1994	68	9
9336013	-3.40	36.70	1372	1935	2005	71	60
9336014	-3.32	36.45	1585	1935	2004	70	5
9336015	-3.42	36.86	1067	1945	1998	54	9
9336031	-3.33	36.62	1432	1955	1995	41	1
9336033	-3.37	36.63	1387	1953	1995	43	2
9336035	-3.38	36.87	1136	1980	2005	26	16
9336036	-3.30	36.92	1676	1962	1994	33	16
9336039	-3.38	36.68	1402	1966	2004	39	1
9336045	-3.38	36.87	1153	1973	1994	22	2
9336059	-3.50	36.67	1150	1977	1994	18	8
9337002	-3.30	37.22	975	1929	2005	77	9
9337004	-3.35	37.33	813	1929	2005	77	2
9337005	-3.25	37.32	1478	1929	2005	77	11
9337021	-3.23	37.25	1250	1935	2005	71	4
9337028	-3.53	37.33	701	1938	2005	68	2
9337029	-3.40	37.32	762	1937	1995	59	3
9337073	-3.33	37.30	914	1952	1994	43	10
9337078	-3.19	37.10	1249	1954	2004	51	6
9337091	-3.34	37.34	840	1960	2005	46	8
9337098	-3.23	37.32	1463	1964	1991	28	3
9337115	-3.42	37.07	891	1972	2005	34	7
9337116	-3.23	37.35	1456	1989	2005	17	18
9337121	-3.22	37.28	1344	1973	2005	33	16
9337122	-3.47	37.33	876	1974	1994	21	5
9337123	-3.27	37.32	1165	1973	1994	22	1
9337136	-3.25	37.15	1143	1975	1988	14	0
9337140	-3.25	37.35	1371	1976	1994	19	4

Daily rainfall mapping

Qualitative comparison of temporal plots

Figures 2(a–e) suggest that first rains of Masika from Upper Kikulewa, Mount Meru and Sanya around

March are responsible for transporting sediments into the rivers because they peak simultaneously with sediment concentration plots. Another notable observation for Weruweru and Kikafu catchments (i.e. subcatchments located along Mont Kilimanjaro slopes) sediment yield characteristics is that sediment sources become exhausted with time, **Figs 2(a–b)**, as depicted by attenuation of sedigraph from similar rainfall storms. Probably it is because of clay soils in the mountain slopes become exhausted and hence resistant to erosion.

Figures 2(a–b) indicate that Weruweru and Kikafu catchments rainfalls were responsible for transporting sediments most of the time during long rains season “Masika” between April and June, 2005. One may note from **Figs 2(c–e)** that Mount Meru slopes, Upper Kikuletwa and Sanya catchments are responsible for transporting sediments during first short rains season “Vuli” of October and November, 2005.

Figures 2(a–e) are the temporal plots of daily mean suspended sediment concentrations (SS) at 1DD1 and daily rainfall amounts between March and November, 2005 for rainfall stations located at centroid of representative subcatchments.

Quantitative (analytical) approach of comparison between daily rainfall amount and suspended sediment concentrations

It was considered imperative to use analytical tools to remove subjectivity in qualitative assessment of sediment source areas in the catchment based on hydrological variables mapping. Both rainfall and streamflow as total discharge and surface runoff were quantitatively analyzed as discussed below.

Correlation technique was adopted in this study to indicate the responsiveness of sediment concentrations in rivers to the spatial rainfall intensities (**Table 2**). The variables are not expected to be linearly correlated but relative variation of correlation coefficients gives an idea of both spatial and temporal responses. Besides, a strong correction between the variable and sediment delivery response is confirmed if the computed correlation coefficient is higher than the corresponding value from the table at 1% probability level of significance, *p*, (Statsoft, 2006).

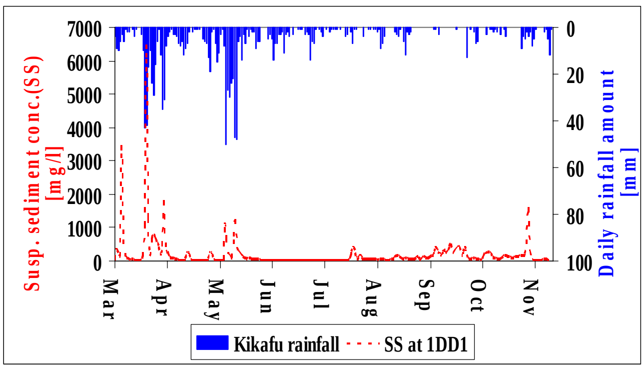

Fig. 2(a) Kikafu at Kibong’oto Hospital rainfall station, code 9337078.

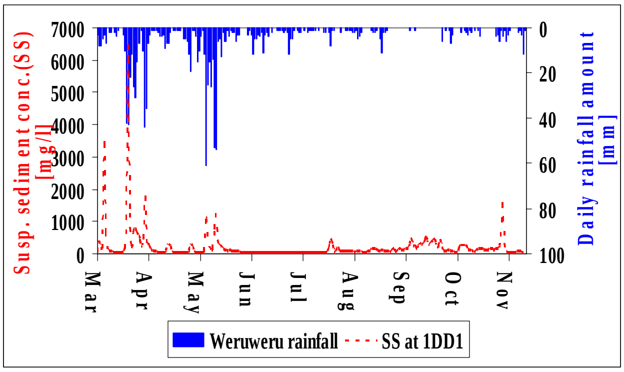

Fig. 2(b) Weruweru at Masama Estate rainfall station, code 93370028.

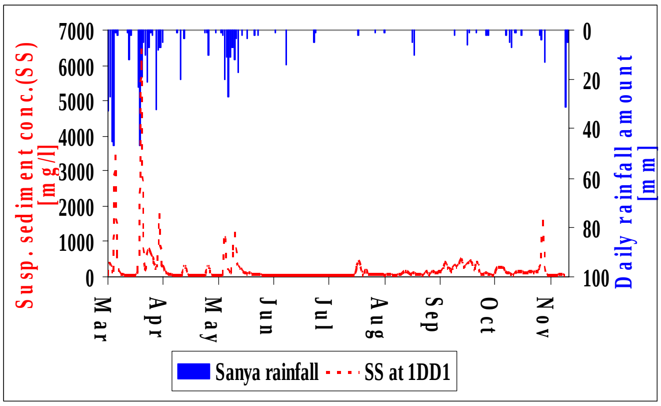

Fig. 2(c) Sanya at Dolly Estate rainfall station, code 93360015.

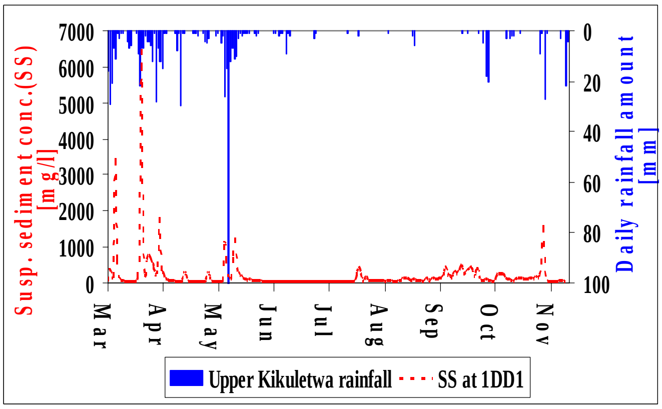

Fig. 2(d) Upper Kikuletwa at Imani Estate Oljoro rainfall station, code 9336059.

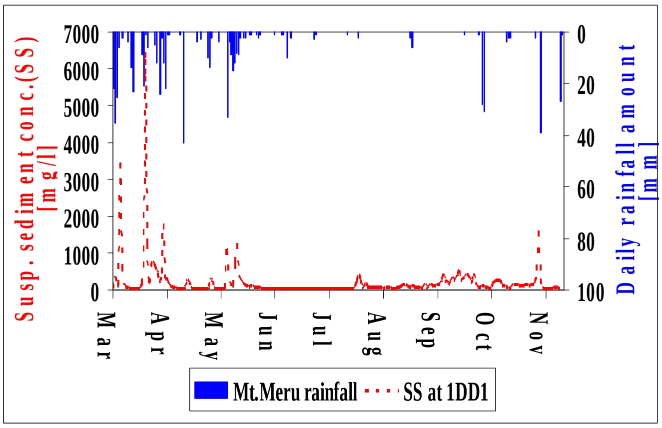

Fig. 2(e) Mount Meru slopes at Themi Estate rainfall station, code 9336013.

A correlation analysis between hydrological variables is also conducted to derive an implied correlation between them and sediment supply sources. A rainfall station for instance, presents both as either a source location or driver for sediment supply to the rivers. Correlation analysis results for the entire sampling period, that is, between 19 March and 22 November, 2005 in **Table 2** indicate that Weruweru and Kikafu catchment rainfalls are significantly correlated to sediment concentrations most of the time (i.e. r = 0.50 and 0.48, respectively).

One would note from **Table 2** that sediment concentrations are significantly correlated with Weruweru and Kikafu catchments daily rainfall and poorly correlated with Meru, Sanya and Upper Kikuletwa rainfalls during a start of long rains (i.e. 19 March–15 April, 2005). This result may seem to contradict the qualitative analysis results as presented above, where comparable higher rainfall storms and sediment concentrations were observed between Upper Kikuletwa, Mount Meru and Sanya rainfalls and sediment concentrations at the sampling site. During the long rains (i.e. 16 April–1 June, 2005), sediment concentrations are highly and significantly correlated with Weruweru and Kikafu catchments daily rainfalls, r = 0.80 and 0.75, respectively. However, one would note that even Mount Meru slopes and Sanya rainfalls are significantly correlated to sediment delivered at catchment outlet.

This suggests that with the exception of Upper Kikuletwa catchment various parts of the catchment contribute sediments to the outlet during the wet seasons. First short rains (i.e. 1–22 November, 2005) from Mount Meru slopes and Upper Kikuletwa catchments are significantly correlated to early sediment transport with r = 0.74 and 0.66, respectively. In this period, evidently based on correlation coefficients, with r < 0.04, which is well below the corresponding table value at 1% probability level of significance by one order of magnitude Weruweru and Kikafu catchments might not contribute sediment to the river system. This is also supported by field work observations by the authors whereby during this time of the year no runoff from Weruweru and Kikafu catchment contribute to the 1DD1 sampling station.

Table 2. Correlation coefficients, r, between spatial daily rainfall amounts and daily mean suspended sediment concentrations at 1DD1 sampling site for different seasons of the year 2005

	Seasons	Value of 'r' at p = 1%	Daily rainfall amounts at representative stations				
			Mount Meru slopes	Upper Kikuletwa	Sanya	Weruweru	Kikafu
Daily mean Suspended Sediment Concentration at 1DD1 site	19–22 March	0.25	0.15	0.10	0.24	0.50	0.48
	19 March–15 April	0.48	-0.17	0.06	0.03	0.50	0.52
	16 April–1 June	0.28	0.35	0.09	0.39	0.80	0.75
	1–22 November	0.45	0.74	0.66	0.27	0.00	0.04

(Note: p is a probability level of significance)

This is compounded by the fact that this area has intensified irrigated agriculture and therefore runoff from a few drops of rainfall is abstracted completely on its way downstream. Besides, from this study one would learn that not all rains yield sediments especially from Mount Meru slopes and Upper Kikuletwa catchments. For instance during the start of long rains season the variables as shown in **Table 2** are poorly correlated, with r = -0.17 and 0.06, respectively. This may suggest that short rains in these sub-catchments deplete sediment sources. After first rains, probably the exposed bare lands are covered by vegetations and hence resistant to erosive agents.

Also this study investigated the influence of suspended sediment residence times (i.e. travel lag time). It should be noted that some rainfall stations in **Table 1** (Mount Meru slopes and Upper Kikuletwa) are located at greater distances (i.e. more than 120 km) from 1DD1 sampling site. Therefore, the correlation analysis was conducted on lagged daily rainfall amounts for the distant stations. Rainfall data for nearer stations (Sanya, Kikafu and Weruweru) were not lagged. The overall results indicate that Weruweru and Kikafu rainfalls are still strongly correlated with suspended sediment concentrations at 1DD1 sampling site most of the time as noted earlier. However, no rainfall station correlates with suspended sediment delivery in the first rains season (1–22 November, 2005).

Probably, the poor correlation in the latter season as a result of rainfall lagging exercise suggests either of two things: (a) that most of the suspended sediment load reaches the 1DD1 sampling site within one day; (b) that daily rainfall amount recorded at 9:00 hours and presented in calendar date already represents a lagged rainfall data. Therefore, the results as derived in **Table 2** were considered as satisfactorily representative.

Daily streamflow and surface runoff mapping

It should be noted that in this study surface runoff was considered as sediment entrainment agent in the upland catchment. Therefore, it is used here below as a good surrogate to sediment concentration and rainfall intensity. However, both total streamflow and surface runoff are used for comparative purposes.

Correlation coefficients between 1DD1 streamflow discharges and daily rainfall amounts of Weruweru and Kikafu catchments are r = 0.60 and 0.58, respectively, between 19 March and 22 November, 2005; r = 0.51 and 0.46, respectively, between 19 March and 15 April, 2005; r = 0.60 and 0.58, respectively, between 16 April and 1 June, 2005; and poorly correlated, r < 0.36, between 1–22 November, 2005. Poor correlation coefficients between streamflow discharges and daily rainfall amounts for Mount Meru slopes, Upper Kikuletwa and Sanya catchments are noted. Streamflow and sediment at 1DD1 site are highly correlated (r = 0.66) during the wet season (i.e. 16 April and 1 June, 2005).

Sediment response was also examined in the context of stormflow (quickflow) or surface runoff, which have been postulated by other workers as a possible delivery mechanism (Rieger *et al*., 1988). Surface runoff time series was obtained by filtering the original discharge series using a baseflow filter developed by Arnold & Allen (1999). Similar observations as noted above do repeat. However, correlation coefficients for long rains season (16 April and 1 June, 2005) has increased to r = 0.68. Although rains of early November have been attributed to causing high sediment concentrations peaks during this period (**Table 2**), low streamflow peak observed in **Fig. 3** suggests that these sources are so localized in terms of area coverage and probably are exposed bare lands or loose soils/highly erodible soils.

Temporal plot in **Fig. 3** suggests that within channel sediment sources such as river bed upstream of 1DD1 station are insignificant, because sediment concentrations become exhausted even if flow discharge is sustained in the river reach. Probably, localized rainfalls and sediment sources might be responsible for suspended sediment concentration peaks during low flows that are between July and October, 2005.

Based on qualitative analysis of **Fig. 3** one would deduce that gully erosion process is insignificant, because sediment peaks do not lead the flood peaks, substantially.

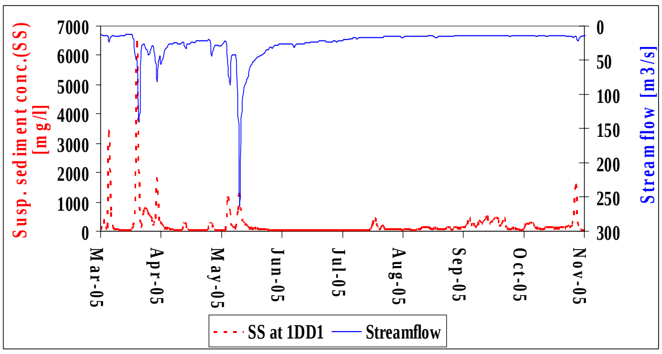

Fig. 3 Temporal plots of daily mean streamflow and mean suspended sediment concentrations (SS) at 1DD1 gauging station.

VALIDATION WITH OTHER METHODS

The study by Ndomba (2007) found that high organic matter content and fine-grained characterize the sediment contents delivered at outlet. Using fingerprinting technique top layer A-horizon or Sheet erosion process dominates in 1DD1 catchment. Besides, sediment sources are headwater regions where both farming and animal keeping activities are practiced. These are Weruweru, Kikafu and Mount Meru slopes catchments. Rating loops analyses indicates that counterclockwise hysteresis dominates over clockwise loops, 11 against 3, from 14 analyzed single hydrological events especially during the wet season suggests that far sources from the sampling site are responsible as major sediment supply in the catchment.

Based on Particle Size Distribution analysis from sediment samples in rivers and reservoir downstream and mapping of catchmemt soil types, clays originating from localized regions of Mounts Kilimanjaro and Meru slopes are attributed to causing this pattern of sediment transport in Pangani River. From aerial photos interpretation and modeling techniques it was found that growing gully features are few and localized in some mountain foot slopes of the catchments (Ndomba, 2007).

One would note that the results of hydrological mapping have been satisfactorily validated with other sediment sources and erosion processes identifying approaches. Besides, the result is comparable to previous researchers' findings in the Pangani River basin that mapped the erosion zones using simple empirical and complex physics-based mathematical models (Mtalo & Ndomba, 2002; Ndomba, 2007). For instance, based on long-term Soil and Water Assessment Tool (SWAT) model simulation, within channel sediment sources contribution is only 3.2% of the 1DD1 subcatchment sediment yield (Ndomba, 2007). This is to say the sediment transport along 1DD1 catchment river channel is in equilibrium state. Besides, spatial simulations of soil loss using Universal Soil Loss Equation built in SWAT model has independently shown that erosion rates are higher in agricultural land use (Ndomba, 2007).

TRANSFERABILITY OF RESULTS TO POORLY GAUGED SUBCATCHMENT, RUVU AT 1DC1

This study could not afford to install automatic pumping sampler at Ruvu subcatchment, 1DC1, because of two main reasons. Lack of adequate funding for purchasing ISCO 6712 machine for the site, and unsuitable hydraulic condition of the river required for ISCO pumping sampler. As a result, most of the techniques presented above were not applied directly to this catchment, rather a comparative assessment of sources and processes based on literature and findings in

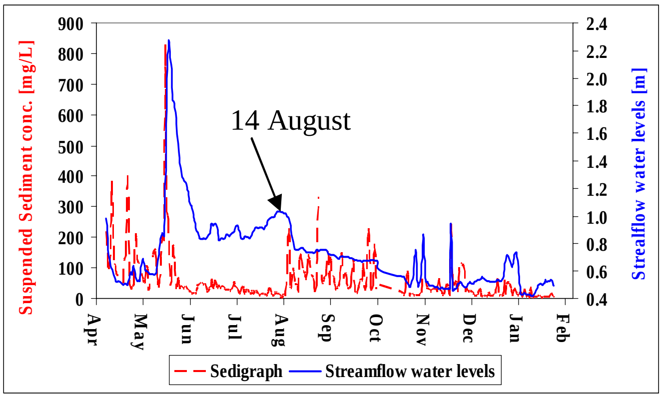

Fig. 4 Temporal plots of daily streamflow gauge heights and suspended sediment concentrations (SS) sampled at 9:00 hours for 1DC1 gauging station, between April 2005 and January 2006.

1DD1 catchment were explored. The discussions below are mainly based on **Fig. 4**.

One would note that late April, 2005 sediments concentration spikes are observed in the falling limb of the hydrograph. This suggests for bank erosion sources and processes. Mid May, 2005 a flood with sediment concentration peak of 830 mg/l leading the flow discharges peak and falls sharply while the spread of hydrograph is wider. As noted at 1DD1 site that sediment transport concentrations in the catchment are so variable within a day or a few days, thus such a repeated pattern at 1DC1 suggests that the sources of sediments for both sampling stations might be the same that is Mount Kilimanjaro foot slopes. In the period between June and July, 2005 streamflow gauge heights are high but sediment concentration is kept low. The period is longer than the 1DD1 case, and probably this suggests that clear sediment runoff waters from Lake Jipe located upstream sustain the flow with little or no sediment supply.

Series of sediment concentrations spikes characterize a period between August and early October though water levels were steadily declining. There is an indication that runoff contribution from main source of water, i.e. Lake Jipe is declining. Tributaries with headwater at Mount Kilimanjaro slopes such as Himo, and Mue might be associated with these sediment spikes. The same pattern of seasonal sediment transport was observed within the same period at 1DD1 and there also Mount Kilimanjaro slopes were linked to as sediment source areas.

Mostly cascades of stream flow spikes with unrecognized pattern of sediment transport characterize a period between November and December, 2005. Runoff waters might be generated from intervening catchment such as Kisangiro.

But the sediment contribution from this catchment is not much compared to unit runoff from tributaries with headwaters at Mount Kilimanjaro. A few examples of where sediment peak lags the streamflow peak are depicted in **Fig. 4** on 14 August, 2005. Probably, the interactions with other factors such as backwater curves have suppressed this dominant pattern of sediment transport at 1DC1 station.

CONCLUSION

The study has found that the major erosion processes is sheet erosion from agricultural fields in the headwater regions of PRB as sediment sources. These are zones of maximum biological activity - the topsoil (i.e. A-horizon) or plow layer in slopes of Mounts Kilimanjaro and Meru slopes.

Spatial and temporal mapping of hydrological variables approach has complemented the results of various renowned sediment sources identification techniques. The introduced method gives not only probable sources and processes but also it additionally identifies location based sediment sources using rainfall stations as pointers. However, it has been learned from this paper that for in-depth understanding of the erosion sources and processes at the catchment level the hydrological variable mapping technique should not be applied in isolation. The result from this study is comparable to previous workers' findings (Mtalo & Ndomba, 2002; Ndomba, 2007) in the same basin.

Although, some methods adopted in this study lacked high resolution data as recommended by other workers, still the author believes that the method applied in this study is quick, reliable and can give more insight to erosion-sediment yield modelling efforts at a catchment level in the follow up studies. The output of the proposed approach in this paper may be used to guide erosion-sediment yield models selection and applications. For instance, a distributed watershed sediment yield model would be appropriate for high spatial and temporal variation of the hydrological variables as noted in this study. Also, the results suggest that Sediment yield model that simulates sheet erosion would be an ideal tool since the major sources of the sediment transported are topsoils.

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