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SOIL EROSION AND SEDIMENT YIELD FROM THE DEGRADED MZINGA RIVER CATCHMENT IN ULUGURU MOUNTAINS, TANZANIA

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ABSTRACT

This paper reports the results of a project started in 2003/04 undertaken to rehabilitate the degraded Mzinga River catchment in Morogoro region, Tanzania by practicing agroforestry ti improve the environment health and the socio - economic well-being of the local community. The land user free choice catchment conservation approach was used. Soil erosion measurements and sediment yield modelling were done to monitor land use practices that contribute to catchment degradation. The results showed very high soil erosion losses on agricultural lands (33 tons/ha) and low soil losses from fallow (4.8 tons/ha) and degraded miombo woodlands (2.4 tons/ha). High soil losses from fields contribute greatly to high sediment loads in the Mzinga river averaging about 17 tons/ha per year. The soil erosion rates on agricultural land and the sediment yield rates from the catchment show the importance of instituting corrective and sustainable conservation measures to ensure clean water supply to downstream uses and sustainable land resources development projects.

KEYWORDS: Catchments rehabilitation /conservation - environmental conservation - sediment yield rates - tree planting

INTRODUCTION

Soil erosion and land degradation are serious problems in Tanzania, especially in the central semi-arid areas and the steep slopes in mountainous areas which are highly populated and cultivated like the Uluguru Mountains. Soil erosion in the Uluguru Mountains has been reported to start in the early 19th century (Maack, 1996, Temple, 1973). Since then, efforts by local communities and governments were initiated to address the problem. However, there has been little, if any success of the initiatives, and the problems of soil erosion and land degradation has continuously increased. The factors that contributed to the failure of the conservation efforts include uncertainties of land ownership, poor performance of the instituted conservation techniques (e.g. bench terraces constructed immediately after the second world war of 1939 to 1945), struggle against colonial domination, and continued and increased impoverishment (Maack, 1992, Temple, 1973).

The causes of increasing soil erosion and land degradation in the Uluguru Mountains, and other mountainous areas of Tanzania are tree cutting to meet increasing firewood and charcoal demands, inappropriate agricultural practices, and shortage of suitable land for cultivation. The high soil erosion rates leads to serious land degradation, increased sediment loads in streams and rivers, leading to rapid siltation of water reservoirs. Land degradation lowers productivity and exacerbated poverty to the local communities. The continuing threat of land degradation makes land rehabilitation important. The rapid siltation of water reservoirs (e.g. Mindu dam) makes sediment yield prediction important.

The Uluguru Mountains form part of the Eastern Arc Mountains of East Africa and have been identified among the four Biodiversity Hot spots of Africa, but are also the source of water for Morogoro and Kibaha municipalities, Dar es Salaam city and all the communities located in the Ruvu river basin. Furthermore, they provide water for irrigated agriculture in Coastal region, Dar es Salaam, and Morogoro. The Mzinga river catchment studied supplies about 70% of the Morogoro Municipality water requirement apart from supplying other areas mentioned above. Thus, the project was started to contribute to sustainable water supply to Morogoro Municipality, sustainable utilization of land resources, improved well being of the local communities and to the global initiative to protect the biodiversity in hot spots.

The Mzinga river catchment study had two implementation components. One of the components dealt with the rehabilitation and conservation of the catchment through afforestration, agroforestry, and other conservation practices. The other component dealt with assessment of soil erosion rates, sediment concentrations in river flows and sediment yields modelling to serve as a tool to monitor the degradation processes and the performance of conservation measures being instituted.

Different techniques varying in costs, sophistication, and accuracy, can be used to measure soil erosion in catchments (Morgan, 1988, Hudson, 1981). The sediment trap method was selected for this study because it is simple, non-expensive, and gives fairly useful results. Prediction of sediment yields from catchments can be by rating curves, extrapolating measured erosion rates on representative land use areas multiplied with sediment delivery ratio (SDR), sediment yield prediction equation, or soil erosion models. Rating curves for rivers and streams are not readily available in many developing countries, including Tanzania. Erosion measurements in catchments are expensive, time consuming, thus are not common in the developing countries. The available sediment yield models are statistical expressions relating rainfall characteristics in the catchment and its topography to sediment yield (Al Kadhimi, 1982; Fournier, 1960, and Fleming, 1969 cited in Morgan, 1988), parametric equations (Williams, 1975), or physically based models (Nearing *et al.,* 1989; Morgan, 1994). The statistical equations give soil erosion indices, thus do not give good estimates of sediment yields. The available parametric equation is the modified universal soil erosion equation (MUSLE) (Williams, 1975). The MUSLE needs runoff discharge and volumes for determining its erosivity factor. These parameters are not readily available in Tanzania, thus, the model could not be used in this study. The available physically based soil erosion and sediment yield models include the WEPP (Nearing *et al*., 1989) and the EUROSEM (Morgan *et al*., 1994). These equations need data base (e.g. catchment runoff discharge, rainfall intensity, and/or rill and interill soil erodibility) which is not available in Tanzania and other developing countries (Mulengera and Payton, 1999). Therefore, they are not useful under Tanzanian conditions. The available empirical soil erosion models include the revised universal soil loss equation (RUSLE) (Renard *et al.*, 1991; Wishmeier and Smith, 1978) and the soil loss estimation method for southern Africa (SLEMSA) (Elwell and Stocking (1982). This study being reported adopted the RUSLE (equation 1) because it has been tested and found to be suitable under Tanzania conditions (Mulengera, 1996; Mulengera and Payton, 1999).

$$A = R \times K \times LS \times CP \qquad (1)$$

Where, A is soil loss (t ha^{-1} yr^{-1})

R = rainfall erosivity (MJ.mm/ha.h),
K = soil erodibility (t.ha.h/ha.MJ.mm),
LS = topographic factor (dimensionless),
CP = vegetation cover and conservation practice factor (dimensionless).

There are two approaches of using empirical soil erosion models like the RUSLE in predicting sediment yields from watersheds. The first approach involves using the sediment delivery ratio (SDR) and modifying the calculation procedure of the model factors in order to transform the catchment into an equivalent plot (Williams and Berndt, 1972). The second approach involves dividing the watershed into morphological areas into which all elementary factors of the selected erosion model can be evaluated (Ferro *et. al.,* 2001). This procedure allows the calculation of soil loss in each morphological area (unit) that is coupled with disaggregated criteria for estimating sediment delivery processes and the unit's SDR to obtain the sediment yield spatial distribution. The disaggregated criteria are determined through measurements of sediment yields from the catchment in question (Ferro *et. al.,* 2001). This approach is not applicable in countries like Tanzania where data on sediment yields from catchments are not available.

The SDR used in the first approach is influenced by a wide range of geo-morphological and environmental factors. However, developed empirical equations for predicting this parameter show the catchment area to be a dominant control although research results relating the SDR with drainage area have produced a bund of SDR variations for a given catchment area. For example a catchment area ≤ 0.01 km^2 has SDR ranging from 0.9 to 1.0 and a catchment area of 1000 km^2 has SDR ranging from 0.05 and 0.9 (Walling, 1983, cited in Walling, 1988).Despite these variations, the American Society of Civil Engineers (ASCE, 1975, cited in Walling, 1988) equation presented below was adopted for estimating the SDR.

$$SDR = kS^{n} \qquad (2)$$

Where, k and n are constants equal to 0.5 and -0.125 respectively, and

S is the catchment area (km^2).

When estimating the sediment yields from catchments using the RUSLE the soil erodibility, topographic factor, and the cover and conservation factors of the equation need to be transformed to catchment scale (William and Berndt, 1972). The soil erodibility transformation to catchment scale is:-

$$K = \sum_{i=1}^{n} \frac{K_i DA_i}{DA} \qquad (3)$$

Where, K_i is erodibility value for soil 'i' in the catchment;

DA_i is sub-drainage area covered by soil 'i';

DA is total catchment (drainage) area, and n is the number of soils in the catchment.

The average catchment slope gradient, s (%) is obtained as (Williams and Berdt, 1972):-

$$s = \frac{H\left\{\frac{1}{2}(LC_1 + LC_{n+1}) + \sum_{i=1}^{n} LC_i\right\}}{DA} x100 \qquad (4)$$

Where, H is the difference in elevation between contours;

LC_i is the length of contour "i" in the catchment,and

n is the number of areas between contours within the catchment.

Williams and Berndt (1977) proposed to use lengths of contours located at 25 %, 50 %, and 75 % of the catchment relief resulting into an equation that is simple and easier to use on larger steep catchments.

$$s = \frac{0.25Z(LC_{25} + LC_{50} + LC_{75})}{DA} X\ 100 \qquad (5)$$

Where, Z is total watershed height,

LC_{25}, LC_{50}, and LC_{75} are contour lengths at 25, 50, and 75 percent of Z respectively.

The average catchment slope length λ is determined as:-

$$\lambda = \frac{LC \times LB}{2EP_i \sqrt{(LC^2 - LB^2)}} \qquad (6)$$

Where, LC is total length of all contours;

LB is length of contour base lines touching points on contours that are farthest from the catchment divide;

EP is the number of extreme points on contour (i.e. points where streams or pronounced natural depressions cross contours).

Once the s and λ parameters are determined then the RUSLE's topographic (S and L) factors are calculated accordingly.

The average cover and conservation practice factor, CP is calculated as:-

$$CP = \sum_{i=1}^{n} \frac{C_{ij} P_i DA_i}{DA} \qquad (7)$$

Where, C_{ij} is cover factor for month "j" for the crop on sub-area "i";

P_i is conservation practice factor for sub-area "i", and

n is the number of sub-areas in the catchment.

The catchment sediment yield (Y_s) estimation using RUSLE s is:

$$Y_s = SDR \times R \times K \times LS \times CP \qquad (8)$$

MATERIALS AND METHODS

The Study Site

The Mzinga River Catchment is located in the Mzinga ward, occupying the steep northwest facing slopes of the Uluguru Mountain range at 6^0 53' S and 37^0 39' E on the southwest periphery of the Morogoro Municipality. Its elevation ranges from about 500 meters above sea level (masl) to over 2100 meters above sea level (masl) (Fig. 1). The Mzinga River catchment has very steep slopes (i.e. over 85 % of the catchment has slopes > 65 %) and is densely populated. Deforestation rate is high, and is mainly due to shifting cultivation (even along the river banks), and annual bush fires. The catchment area is about 22.6 km^2. The upper 30 % of the catchment (900 ha) is under Montane rain forest. Below the forest are human settlements, cultivated fields, and semi-natural and/or degraded miombo woodland vegetation on uncultivated hill slopes and river valleys. The catchment drains into Ngerengere River and Mindu dam that is about 3 km from Morogoro Municipality centre along the road that links Iringa Municipality and the Dar es Salaam city. The overflow from the Mindu dam joins other tributary rivers (e.g. Morogoro River) from the Uluguru Mountains that finally form the Ruvu River draining to the Indian Ocean between Dar es Salaam city and the Bagamoyo historical town

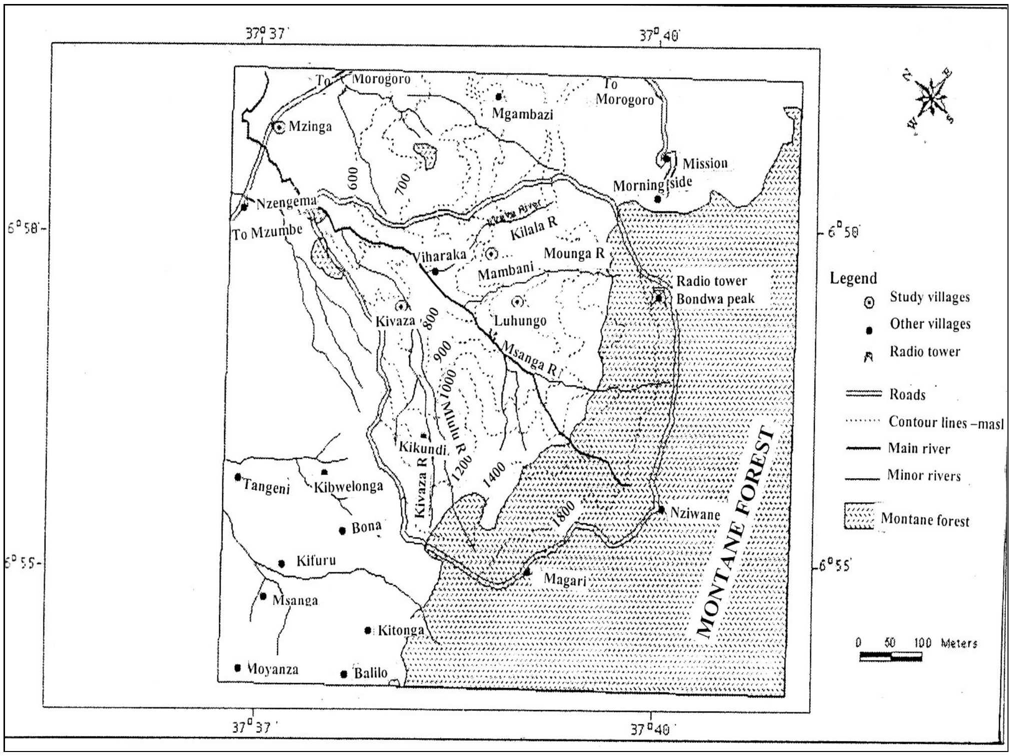

Figure 1 Upper Mzinga River Catchment in Uluguru Mountains, Morogoro, Tanzania

Data collection

Soil erosion

Levels of soil erosion were monitored on selected catchment land areas (cultivated, fallow, and degraded miombo woodland areas) using sediment traps (Hudson, 1981; Morgan, 1988). The cultivated areas were multi-cropped with pigeon peas, maize and cassava. The land slope lengths and gradients for the trap sites were determined using a tape and a clinometer, respectively. A suitable river cross section with bedrock was identified upstream of the SUA and Mzinga Corporation water intakes. The cross section profile was determined using engineers level. Three water stage gauge meters were installed at different levels along the cross section for water flow depth monitoring. River flow velocities at appropriate depths of flow were measured using current meters for set days (Shaw, 1985, Morgan, 1988). Readings from the gauge meters and current meters were used to calculate river discharges. Sediment samplers were used to take samples from the river discharges for determination of sediment concentration at the set times (Morgan, 1988).

Transect walks were done for the upper Mzinga River catchment and the adjacent upper Morogoro River catchment that is on the east to determine field soil colour, texture, and structure of similar soils in the two catchments. This enabled determination of the Mzinga River catchment soil erodibility values based on the Morogoro River catchment soil erodibilty values that were determined using texture laboratory analysis data (Mulengera and Payton, 1999; Rapp *et al.,* 1972). The two adjacent catchments have approximately the same topography, drainage pattern and area, shape, and have same soil parent materials, thus were found to have similar soil types.

Secondary information on land cover, land use, soils and topographic maps were collected from Sokoine National Agricultural Library (SNAL), the Mapping Unit – Ministry of lands Dar es Salaam, and the paper by Rapp et al., (1972).

Sediment samples analysis and sediment yield prediction

One litre samples of runoff and eroded soil caused by one storm or few storms not resulting in trap overflows were collected from the sediment traps after vigorous stirring and taken to laboratory for oven drying at 105 ^{0}C for 24 hours, weighing, and determination of sediment amounts. The total sediment loads in the traps were then calculated using the recorded runoff volumes for each trap. The slope length and trap widths together with the sediment loads were used to estimate soil erosion on hectare basis.

The sediment yield prediction was carried out using equations 2 to 8. The delivery ratio, SDR for the catchment was obtained from the graph plot of SDR values and drainage areas (Walling, 1988). Equation 5 was used in this study to calculate catchment slope gradient because of the steep slopes of the Mzinga catchment and closely spaced contours and large relief, i.e. 1580 m. After determining the slope gradient and length parameters the RUSLE's model equations were used to calculate its topographic factors (Liu *et al.*, 1994; McCool *et al.*, 1987; McCool *et al.*, 1989). The land use type and climate of the Mzinga river catchment were used to estimate the RUSLE's cover, C values (Dissmeyer, 1982, Morgan, 1988). The conservation practice factor for the catchment was taken to be unity because there are no physical conservation practices that are used. The catchment cover and conservation practice factor, CP was then calculated using equation 7. Finally the sediment yield prediction for the catchment was determined using equation 8.

RESULTS AND DISCUSSION

Table 1 shows soil erosion rates from the four sediment trap sites. Soil losses from cropped fields are very high, ranging from about 32 to 83 kg per rainy season. They indicate a maximum soil loss of about 33 tons/ha. This is more than 6 times the maximum allowable rates of about 5 tons/ ha per year (Schertz, 1983); making land utilization unsustainable. Kimaro (2003) reported soil losses ranging from 91 to 258 tons/ha/year from fields in the adjacent upper Morogoro river catchment. Soil losses from degraded miombo woodland range from 1.7 to 6.4 kg and that from fallowed land ranged from 0.5 to 7.7 kg. The seasonal rainfall of 2005/06 (1112 mm) was higher than that of 2004/05 (976 mm) and well distributed resulting in denser vegetation cover and less soil loss as shown in Table1. However, maximum soil loss from the miombo woodland during the two seasons was 4.8 tons/ha and that from the fallow lands was 2.4 tons/ha. The results show that soil losses from cultivated lands are about 20 times higher than that from the degraded miombo woodlands. When the effects of good vegetation cover of 2005/06 was taken into account, fallowed lands experienced soil loss that was 4 to 118 times less than that from cultivated fields. The low soil losses from both, the degraded miombo woodlands and fallow lands can allow sustainable maintenance of land quality.

Measurements of the river discharges and sediment concentrations were only possible for low flows. Small increases in flow depths after storms resulted in quite high flow velocities due to steep gradients at the gauge station and the catchment in general. This made sediment sampling and gauge reading unsafe and impossible for high and peak flow discharges. The few measured low flow sediment yields were of little use in monitoring sediment concentrations in the river resulting from the catchment soil erosion processes.

The proportions of different land uses and the RUSLE cover and management factors are as shown in Table 2. Montane rainforest and fallow land cover the largest area of the catchment, and cultivated area any cropping season cover15 %. During the three years of tree planting in the catchment (2004 – 2007), 89% of trees (72,119 trees) planted survived and are still growing (Lulandala *et al.*, 2007). Their cover is still insignificant for controlling soil erosion from the Mzinga river catchment. The average RUSLE – C factor for the catchment is as shown in Table 3. The soil erodibility values in the catchment varied from 0.052 (t.ha.h/ha.MJ.mm) for the sandy silt soils found in the montane forest to 0.021 (t.ha.h/ha.MJ.mm) for sandy clay loams found at low and middle altitudes of the catchment.

The calculated average catchment slope gradient and slope length using the equations 5 and 6 were 53% (27.9 ^{0}) and 276 m respectively. These were used to determine the RUSLE topographic values (i.e. S and L) are shown in Table 2. The values are characteristic of the catchment and are comparable to the measured values in Table 1. Because farmers do not use mechanical conservation techniques the conservation practice factor of the RUSLE was assumed to be unity. Annual rainfall in the catchment varies from about 890 mm per year at 550m.a.s.l. to 2400 mm per year at altitudes greater than 1500m.a.s.l. Consequently the rainfall erosivity in the catchment varies from 3,362 (MJ.mm/ha.h) to 11,914 (MJ.mm/ha.h), with an average of 7,512 (MJ.mm/ha.h) as shown in Table 3.

The RUSLE factors in Table 3 when multiplied resulted in predicted average sediment yield of 17.24 (t ha^{-1} yr^{-1}). The sediment yield looks to be representative of sediment yield from catchments in Tanzania which are suffering from severe soil erosion. Christiansson (1981) measured sediment yields of up to 11 tons/ha/year in the Dodoma catchments which are less steep and having soils with low erodibility values (Mulengera, 1996). Rapp *et al.* (1972) developed a sediment discharge rating curve for the adjacent upper Morogoro river catchment using measurements with very limiting peak flows. From the rating curve they estimated annual sediment yields of 4 t/ha. Most of sediments are carried in peak river flows; therefore, their estimate should be lower than the actual sediment yields. Thus, the results from this study are acceptable for use in planning soil conservation and water resources development.

Table 1: Land use, topography, and soil loss in the Mzinga catchment[1]

Site[2]	Land use	Slope Gradient (%)	Slope length (m)	Topographic factor, LS[3]	Soil loss (kg)[4] 2004/05	Soil loss (kg)[4] 2005/ 06
A_U	Degraded miombo woodland	53	26.5	10.7	6.4	0.8
A_D		51	79.1	23.4	2.4	2.3
B_U	Cultivated in 2004/05 &	59	36.9	15.1	74.2	0.5
B_D	Fallowed (2005/06)	62	63.1	23.3	32.0	7.7
C_U	Cultivated in 2004/05 &	67	32.6	15.1	68.7	0.8
C_D	Fallowed (2005/06)	69	49.7	21.3	82.6	0.7
D_U	Degraded miombo woodland	60	52.0	19.7	1.7	0.9
D_D		58	97.2	30.3	3.8	1.0

[1] Rainfall and soil loss records started at the end of November 2004.

[2] Subscrits U &D mean upslope and down slope respectively.

[3] Factor LS was calculated using RUSLE's equation for steep slopes (Liu *et al*., 1994).

[4] Rainfalls recorded near trap sites were 976 mm &1112 mm for 2004/05 & 2005/06 respectively

Table 2 Land use areas in the Mzinga river catchment, and the USLE - C factor values

Land use	Land use characteristics	USLE – C factor	Catchment Area (%)
Montane rain forest	Evergreen, cover > 90 % with rough ground & thick litter	0.0001	30
Degraded miombo woodland	Dense cover >80 % & rough ground	0.0006	25
Fallow land	Dense vegetation (Morgan, 1988)	0.001	30
Cultivated fields	Cropping followed by dense vegetation	0.025	15

Table 3: Calculated RUSLE Factors and Predicted Sediment yield from Mzinga river catchment

R (MJ.mm/ha.h)	K (t.ha.h/ ha.MJ.mm)	S	L	C	SDR (%)	Predicted sediment yield (tha^{-1} year^{-1})
7512	0.037	9.465	5.904	0.003	37	17.24

The average sediment concentrations after rainstorms in montane rainforest streams of the upper Morogoro river catchment were found by Rapp *et al.* (1972) to be at least four times less than those leaving the catchment in non-peak flows at its downstream end. As observed by the researchers in the adjacent Morogoro river catchment, and as shown by trap measurements in Table 1, much of the sediment yield in the Mzinga river catchment comes from cultivated fields with relatively very large C values compared to other land use practices i.e. ≥ 10 times larger than the average catchment value. Therefore, if soil erosion in cultivated fields can be reduced to acceptable levels, the sedimentation of

Mzinga River, Mindu dam and water supply intakes will be controlled. Thus, the approach used in the project to encourage, support, and sensitizes people to plant trees and to practice agroforestry and other conservation practices is pertinent.

CONCLUSIONS AND RECOMMENDATION

Both soil erosion measurements and sediment yield modeling show that the Upper Mzinga Catchment is experiencing high rates of soil erosion. Measurements results showed that soil loss from cultivated fields was higher than that fro fallow lands and degraded miombo wood lands. The soil loss from cultivated fields was about 6 times higher than the allowable soil loss rates for the type of soils found in the catchment. Thus, establishment of appropriate conservation measures on agricultural fields (e.g. agroforestry, fertility management and etc.) are pertinent and should be rigorously continued. The project activities of rehabilitating the entire catchment through tree planting and promotion of various conservation practices should be continued with stepped up efforts.

The results also show that combining soil erosion and sediment yield modeling in field conservation measures under Tanzanian conditions can be useful in determining the effectiveness of the applied conservation techniques. Since siltation of reservoirs, water supply systems, and irrigation structures is a serious problem in Tanzania, soil erosion and sediment yield modeling is a useful tool in addressing these problems.

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