Modelling of Sedimentation Upstream of Nyumba Ya Mungu Reservoir in Pangani River Basin

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Abstract

This paper is reporting the preliminary findings of a research on modelling sedimentation in large complex catchments. The study objectives were achieved by developing a conceptual framework. The study case is a regulated Nyumba Ya Mungu (NYM) Reservoir catchment in the upstream of Pangani River Basin (PRB) located in the North Eastern part of Tanzania. It should be noted that in literature there are no compelling methods and tools for the purpose. The framework developed for this study, therefore, comprised of a conceptual model and a network of sediment properties and yield fluxes monitoring sites across the basin. The conceptual model was set up by linking a comprehensive distributed, physics based, mathematical watershed model, Soil and Water Assessment Tool (SWAT), and a set of rule based stepwise regressive models. Regression analysis was conducted under Data Mining Tool (Cubist) environment. A sampling network embodies field measurements of upland catchment erosion rates, continuous Suspended Sediment Concentrations (SSC) and Soil Organic Matter (SOM) content sampling programme in the upstream major river tributaries and downstream reservoir bathymetric survey. The feedback loop between the components of the conceptual framework was developed and used. The study results suggest that modelling activities should be well guided by analysis of field-based data in order to reduce the uncertainties involved in sedimentation studies. Besides, the various components of the modelling framework must complement each other. This study used one hydrological year sediment sampling programme data successfully to identify erosion sources/ processes and predict long term annual average of NYM reservoir sedimentation rate. Testing of the developed conceptual framework elsewhere is recommended.

Key words: Conceptual model, CUBIST Tool, Modelling, Sedimentation, SWAT

1. INTRODUCTION

A broad and working definition of sedimentation for this study is borrowed from Vanoni (1975). Sedimentation embodies the processes of erosion, entrainment, transportation, deposition, and the compaction of sediment. These are natural processes that have been active throughout geological times and have shaped the present landscape of our world. The principal external dynamic agents of sedimentation are water, wind, gravity, and ice (Vanoni, 1975). Although each may be important locally, only the hydrospheric forces of rainfall, runoff, and streamflow forces are considered in this study.

Existing approaches to modelling natural landform patterns, reductionism and universality, are incompatible with the nonlinear, open nature of natural systems. No consensus exists on how to model natural patterns or, in many cases, the mechanisms by which particular patterns develop. Many models for complex systems are simple and Universalist (Werner, 1999). The advantage of these simple models they are often straightforward to understand. Their disadvantage is that it can be difficult to conduct discriminating tests against natural systems (Werner, 1999). Prosser *et al.* (2000) noted that shear stress or stream power exerted by the flow plays only the secondary role of removing the sediment that has been generated. Thus prediction based on stream power or shear stress alone, which is commonly used for predicting sediment transport, will produce unreliable results (Prosser *et al.*, 2000). Inclusion of a critical shear stress term would not solve the problem and would only highlight the need to include sediment loosening processes to predict observed sediment yields (Prosser *et al.*, 2000).

Most of the available study methods (field measurements or modeling) work well at small basins and preferably at plot scales. They have the disadvantage that their results can not easily be extrapolated to larger basins (Yanda, 1995; Wasson, 2002; Ndomba, 2007). For instance, Rieger *et al*. (1988) reported that small-scale studies have indicated large sediment loads from parts of the slopes and at the same time, total sediments yields at the basin scale are small in comparison. Besides, field measurements as direct methods have been reported by other workers to give un-reliable estimates (Peart and Walling, 1988). According to critical review conducted by Ndomba (2007) to date there is no ideal model yet developed for all hydrologic conditions. Besides, each model has specific limitations, for instance most models in use do not incorporate a gully erosion-modelling component. The latter component is critical for the study area as on the foot slopes of Mount Meru there is evidence of huge gullies as reported in Semu *et al.* (1992). However, models such as European Soil Erosion Model (EUROWISE) (Jetten, 2002) that simulate gully erosion require high-resolution data on temporal and spatial domains, and therefore their applicability in larger and ungauged catchments such as PRB is questionable. Other models such as The Water Erosion Prediction Project (WEPP) (Lane *et al.,* 1992) are promising and may suit for some purposes of this research. They are disqualified because of their huge data requirement. The high-resolution data required to run the Green-Ampt equation in WEPP is not available for PRB. Besides, most of the tropical countries in the Eastern, Central and Southern Africa have no appropriate and accurate soil erosion prediction models (Ndomba, 2007; Ndomba and Birhanu, 2008). Currently these countries use Soil Loss Estimation Model for Southern Africa (SLEMSA) and the Universal Soil Loss Equation (USLE) developed in Zimbabwe and USA, respectively. The SLEMSA still needs some modifications and has, so far, not been widely used or tested outside Zimbabwe and in some instances have shown to give unrealistic soil loss values, Mulengera (1999).

A conceptual framework is used to outline possible courses of action or to present a preferred approach to a system analysis project (Botha, 1989). The framework is built from a set of concepts linked to a planned or existing system of methods, behaviours, functions, relationships, and objects (Botha, 1989). A conceptual framework might, in computing terms, be thought of as a relational model (Botha, 1989).

Based on the foregoing discussions one may conclude the following: there are no compelling methods and tools on sedimentation studies and uncertainty in sedimentation modelling is high and inevitable using the available study techniques. Since there were no compelling methods and tools to research on the problem, this study developed a conceptual framework for PRB for the purpose. It should be noted that the details of the various components of the conceptual framework could be consulted in (Ndomba, 2007).

Therefore the objective of this study was to propose and verify the applicability of a conceptual framework for sedimentation modelling studies in large complex catchments using short term sampling programme data.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

The Pangani River Basin (PRB) is located in the North Eastern part of Tanzania and covers an area of about 42,200 km^2, with approximately 5% in Kenya (**Figure 1**). In Tanzania, the Basin is spread over four administrative regions: Kilimanjaro, Arusha, Manyara and Tanga. The Pangani River has two main tributaries, the Kikuletwa and the Ruvu (**Figure 1**), which join at Nyumba Ya Mungu (NYM), a reservoir of some 140 km^2. The effluent of the reservoir is known as the Pangani River, which flows for 432 km before emptying into the Indian Ocean. The NYM Reservoir is the largest water body in the Basin. There are three others: Lake Ambusseli and lying on Tanzania's border with Kenya, lakes Chala and Jipe (**Figure 1**). The PRB is thought to have about 90,000 ha of swamp, most of which comprises the Kirua Swamps, lying downstream of the NYM Dam.

Other swamplands are the Ruvu Swamp that lies at the point where the Ruvu River exits from Lake Jipe, and a swamp lying within main Ruvu and Kikuletwa Rivers flood plains and bordered to the South by NYM reservoir. The latter swamp area is said to cover some 40 km^2.The study area covers the upstream of NYM Reservoir (**Figure 1**). The catchment of NYM dam occupies a total land and water area of about 12,000 km^2 (Ndomba, 2007). It is located between Latitudes 3^{o}00'00" and 4^{o}3'50" South, and Longitudes 36°20'00" and 38°00'00" East. This area has an Average Annual Rainfall (AAR) of more than 1000 mm/yr. 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). High levels of precipitation can be found in the southern slopes of the mountain areas with AAR of 1000-2000 mm/year. 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. More than 50% of the basin, mainly the lowland plains are arid or semi-arid with an AAR of 500-600 mm/year. A few large springs contribute with a yield of 15-20 m^3/s, and these form a major part of the inflow to the NYM reservoir (Rohr, 2003). For instance, Chemka springs with an almost constant flow of nearly 10 m^3/s and Miwaleni springs 10 m^3/s (Rohr, 2003). Seasonal variation of temperature in the basin ranges from 14°C to 25°C. Maximum and minimum temperatures occur between March and July, respectively. The upper PRB is characterized by relatively high potential evaporation varying from 700 mm/yr at high elevations to about 1500 mm/yr in low-lying areas. It means that for lower areas, the annual potential evaporation is higher than the annual rainfall (Moges, 2003). The catchment comprises of complex geological formations such as North Pare Mountains, Mounts Kilimanjaro and Meru. The geology of the region mainly consists of Neogene Volcanic and pre-Cambrian metamorphic rocks, which are extensively covered by superficial Neogene deposits including calcareous tuffaceosus materials, derived from the Kilimanjaro volcanic and the deposits around Lake Jipe (Geological Survey, 1960).

The altitude in the study area ranges between 700 and 5825 masl. The ice cap at the peak of Mount Kilimanjaro forms the highest ground in the catchment. Most of the PRB comprises crystalline and limestone geological series, along with patches of lacustrine deposits. Areas close to Mounts Meru and Kilimanjaro are typically highly fertile alkaline volcanics (Geological Survey, 1960). This combination of soils of lacustrine and volcanic origin, as well as areas of high AAR mean that parts of the PRB have come to be seen as the 'breadbasket' of Tanzania. Based on the Soil Atlas of Tanzania, the main soil type in the upper PRB is clay with good drainage. Actively induced vegetation, forest, bushland and thickets with some alpine desert chiefly characterize the land cover of the catchment.

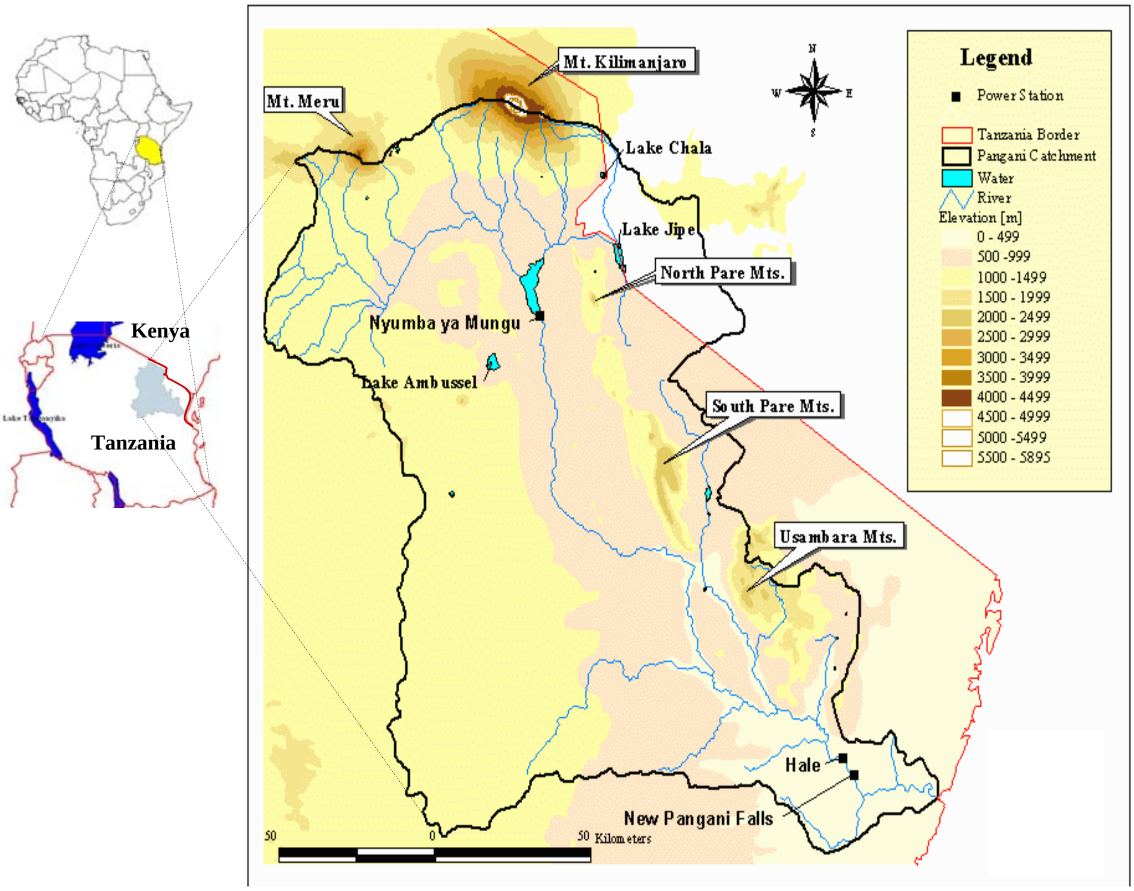


Figure 1: Location of the Pangani River basin.

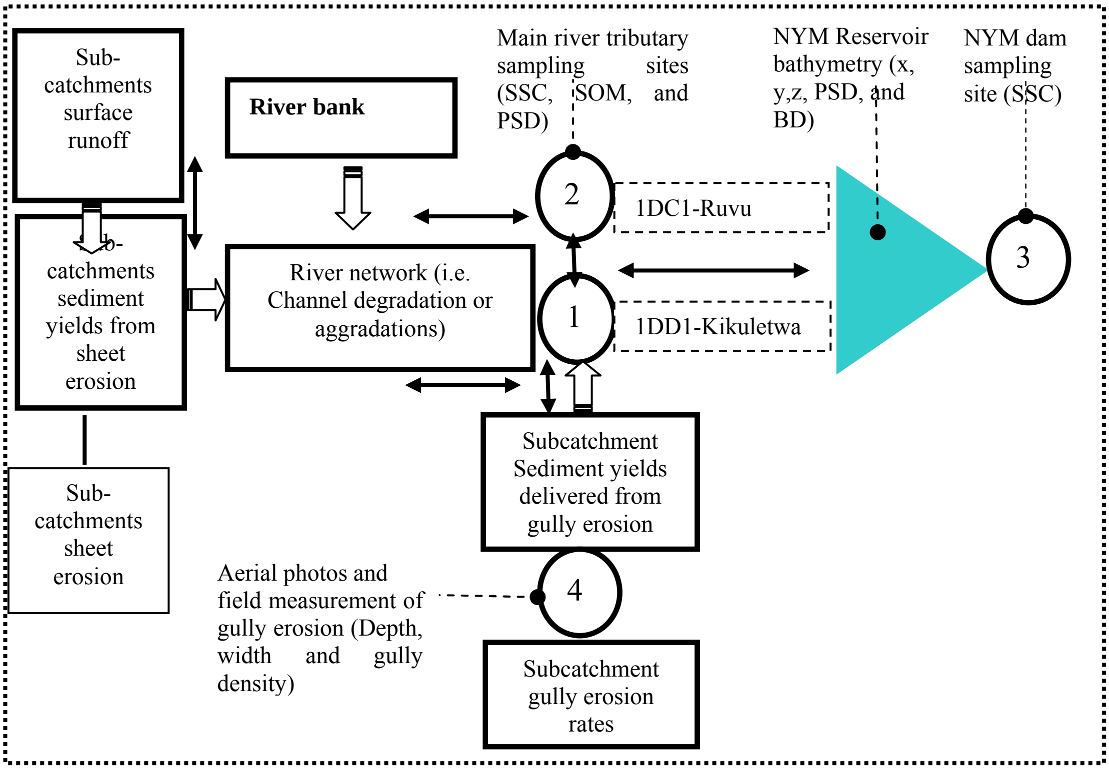
Population densities of more than 600 persons/km^2 are found on the slopes of Mount Kilimanjaro. The mountain slopes of Mounts Meru and Kilimanjaro have some of the best-developed and best-known traditional furrow irrigation systems in East Africa. Extensive irrigation, particularly in the upper part of the basin, secures crops against erratic rainfall on the lowland plains and extends the growing of crops like paddy, maize, banana, beans, coffee, vegetables and sugar cane. The basin is also important for hydropower generation which is connected to the national grid. Hydropower plants, which are downstream of NYM Reservoir are NYM (8MW), Hale (21MW), and New Pangani Falls (NPF) (66MW).

It should be noted here that, the study case was purposively selected. This study intended to test new study methods and applying new modeling tools in the region, availability of historical data for calibration and validation was a crucial criterion. For instance, long term records of hydro-climatic data for the basin and design topographic map of the reservoir bed were central information to the accomplishment of this research work. As discussed above, the study catchment is complex, well regulated by human activities and of national interest to Tanzania. Besides, logistical, accessibility and funding issues were also considered.

Moreover, this catchment has been widely studied (Moges, 2003; Mtalo and Ndomba, 2002; Rohr, 2003; Rohr and Killingtveit, 2003; Ndomba *et al*., 2007) and therefore adequate findings and reports derived from multi-disciplinary approaches of addressing water resources management at a catchment level are available for reference. And the previous findings in the study area have been extensively referred to.

2.2. Development and Application of a Conceptual Framework for the Pangani River Basin

In this study the framework comprises of a conceptual model and a network of sediment properties and yield fluxes monitoring sites (sampling network) across the basin (**Figure 2**). The conceptual model was set up by linking distributed, physics-based sediment yield model and a set of rule based multi-regression models for gully erosion prediction. A feedback loop (i.e. a system where outputs are fed back into the system as inputs, increasing or decreasing effects) as indicated by double arrows in **Figure 2** between components of the conceptual framework was developed and used.



EGEND

Symbol	Descriptions	Symbol	Descriptions
□	A major modeling component	▶	Nyumba Ya Mungu reservoir (NYM)
□	A minor modelling component	↔	A feedback loop pointer
○	Sampling or measurement site and main feedback loop node	⇨	A strong link between modelling components
—	A weak link between modelling components	⬚	A river reach between sampling sites and inlet of NYM reservoir

Figure 2: A conceptual framework for modelling erosion processes and reservoir sedimentation in Nyumba Ya Mungu reservoir catchment.

Note: SSC-suspended sediment concentrations, SOM-Soil organic matter content, PSD-Particle Size Distribution, and BD-Bulk density, 1DC1 and 1DD1- Gauging stations at main outlet of Ruvu and Kikuletwa subcatchments; x,y,z-Positions in Eastings and Northings and elevations of echo sounding data).

Physics-based, spatially distributed modelling systems have particular advantages for the study of basin change impacts and applications to basins with limited records (Bathurst, 2002). Their parameters have a physical meaning and can be measured in the field and therefore model validation can be concluded on the basis of a short field survey and a short time series of meteorological and hydrological data (Bathurst, 2002). Besides, the author used this category of models in order to avoid the linearity, stationarity and lumping assumptions made by other analytical tools such as sediment rating curves.

The Physics based model used in this study is the Soil and Water Assessment Tool, (SWAT) (Arnold *et al*., 1995) for simulating surface runoff, erosion and sediment yields from sheet erosion and channel aggradations and degradations (**Figure 2**). This model has been reported to perform satisfactorily in poorly gauged catchments (Ndomba and Birhanu, 2008). The SWAT model applies water balance Equation (**Equation 1**) as a driver for everything that happens in the watershed (Neitsch *et al*., 2005). The USDA-SCS runoff curve number (SCS, 1972) is used to estimate surface runoff from daily precipitation (**Equation 2**).

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \qquad (1)$$

Where SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \qquad (2)$$

Where Q_{surf} is the accumulated surface runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm), and S is the retention parameter (mm).

Erosion/soil loss and sediment yield were estimated for each Hydrologic Response Unit (HRU) with the Universal Soil Loss Equation (Wischmeier and Smith, 1965) (**Equation 3**) and Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) (**Equation 4**), respectively. The current version of SWAT model uses simplified stream power equation of Bagnold's (1977) to route sediment in the channel.

$$Sed = 1.292 EI_{USLE} K_{USLE} C_{USLE} P_{USLE} LS_{USLE} CFRG \qquad (3)$$

Where Sed is the sediment yield on a given day (metric tons), EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m^2 hr)), other factors are as defined below. The value of EI_{USLE} for a given rainstorm is the product, total storm energy (E_{storm}) times the maximum 30 minutes intensity (I_{30}).

$$Sed = 11.8\left(Q_{surf}\, q_{peak}\, Area_{hru}\right)^{0.56} K_{USLE} C_{USLE} P_{USLE} LS_{USLE} CFRG \qquad (4)$$

Where Q_{surf} is the surface runoff volume (mm), q_{peak} is the peak runoff rate (m^3/s), $Area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and CFRG is the coarse fragment factor. However, it should be noted that in this K_{USLE} for tropical regions are proposed by Mulengera (1999) was used. Input data required to set up a SWAT model include, landuse, soil type, Digital elevation Model (DEM), Rainfall and climatic data.

The runoff and sediment components of the model were calibrated at one of the major rivers tributary called 1DD1-Kikuletwa sampling site, Node 1, (**Figure 2**) (Ndomba *et al*., 2008a, 2008b, 2008c). The sediment component was calibrated from data derived from a sediment rating curve based on short term (i.e. between March and November, 2005) suspended sediment sampling programme. The runoff component was verified from historical stream flows whereas sediment component was validated from long term reservoir sedimentation information. Sheet erosion was estimated and routed from upland catchment through river network to downstream main tributary outlet using SWAT model. As gully erosion processes are not well understood in literature, this study used **Equation 5** below to estimate gully erosion rate.

$$G_r = \frac{1000\rho_b\rho_G D_n W_n A_c}{T_a} \quad \text{.........} (5)$$

Where, G_r is the long term gully erosion rate [t/yr.], D_n and W_n represent net depth and width change of gully feature [m], ρ_b and ρ_G are bulk density of the soil [t/m^3] and gully density [Km/Km^2], A_c is the catchment area [Km^2], T_a is the time period spanning between multi-temporal aerial photos [yr.], and 1000 is a constant for unit conversion. As reported in Ndomba *et al.*, (2009), the overall net change in depth and width across the catchment are 1.09 m and 6 m, respectively. Various soil bulk densities values that range between 1.3 and 1.5 have been assumed by other workers elsewhere (Yanda, 1995; Wilkinson *et al.*, 2004). A value of 1.5 t/m^3 was adopted in this study because it compares well with some typical values of measured bulk densities of the downstream reservoir bed material. It was also checked against the lowest possible value of 1.17t/m^3 of the deposited sediments in the reservoir as reported in Ndomba (2007). A time period between multi-temporal aerial photos of 25 years was computed for this study. It should be noted that these values have been assumed constant for entire catchment. Estimation of gully erosion rate was lumped for each subcatchment on which gully features were predicted. The contribution of gully erosion to downstream catchment sediment yield was estimated using **Equation 6** below.

$$S_G = \frac{SDR * G_r}{100} \quad \text{.........} (6)$$

Where, S_G is the estimated long-term sediment yield rate from gully erosion [t/yr.], SDR is the sediment delivery ratio [%], G_r is the estimated long-term gully erosion rate [t/yr.] and 100 is a constant that converts SDR to decimal number. A delivery ratio of 50% as reported in previous studies by Mtalo and Ndomba (2002) was used in **Equation 6** above to estimate sediment yield from gully erosion
Most of the modelling efforts were directed to estimating the gully density because the author considered it to be the most sensitive parameter in the **Equation 5** above. Other workers such as Hughes and Prosser (2003) adopted the same approach. This study developed rule based stepwise multi-regressive models (**Equation 7**) under data mining tool (Cubist) environment by regressing environmental variables (X_i) as independent variables and gully density (Y) as dependent variable (Ndomba, 2007).

$$Y = a + b_1X_1 + b_2X_2 + \ldots + b_pX_p \quad \text{.........} (7)$$

Where, the regression coefficients (or b_i coefficients) represent the independent contributions of each independent variable to the prediction of the dependent variable. And *p* denotes number of environmental variables that satisfies each condition or rule.

Data mining is an analytic process designed to explore data in search of consistent patterns and/or systematic relationships between variables, and then to validate the findings by applying the detected patterns to new subsets of data (Statsoft, 2006). Data mining is also known as knowledge discovery, machine learning or computational learning theory and the ultimate goal of data mining is prediction (Statsoft, 2006). These methods usually involve the fitting of very complex "generic" models that are not related to any reasoning or theoretical understanding of underlying causal processes; instead, these techniques can be shown to generate accurate predictions in validation samples (Statsoft, 2006). The data mining tool used in this study is Cubist (Rulequest, 2004). Cubist is a tool for generating rule-based predictive model from data (Rulequest, 2004).

Two split samples of about 70 and 30 percent were used for model training and testing, respectively. The correlation coefficients and relative errors were used as criteria to qualify the performance of the developed rule based models.

A sampling network embodies field measurements of upland erosion rates, continuous Suspended Sediment Concentrations (SSC) and Soil Organic Matter content (SOM) sampling programme in the upstream major river tributaries and downstream of the reservoir and bathymetry survey (**Figure 2**). The data collected from the sampling network was independently used to estimate gully erosion rates, the actual fluvial sediment load within the sampling period, long term catchment sediment yield rate.

Besides, the data analysis alone identified y erosion processes and sediment sources (Ndomba, *et al*., 2007). The analysis of data was used to establish a relative proportion contribution between ungauged subcatchment, IDC1-Ruvu and a well gauged subcatchment, 1DD1-Kikuletwa as presented in **Figure 2** (Ndomba 2007). The proportions derived was used to estimate annual sediment yields of poorly gauged catchment based on gauged catchment loads in the period which hydro-climatic data is missing. Therefore, annual sediment loads at 1DD1 could be directly linked to loads at 1DC1. Although, the sediment yield modelling activity was not carried out at 1DC1, a proportion derived was used to transfer the estimated and measured loads at 1DD1 to this site. Besides, identified sediment processes based on data alone guided the modelling activities. As other workers such as Rieger *et al.,* (1988) noted that sediment responses provide both a start and end point for modeling the sediment delivery process. They act as a starting point in that they provide information concerning the possible nature of the delivery process (Rieger *et al.,* 1988; Ndomba *et al*., 2007). They also act as an end point since any model must replicate the responses known to exist in the basins. Given the complexity of response type and spatial-temporal variation of response, modeling the delivery process would, at first, seem a daunting task (Rieger *et al*., 1988). However, some of this complexity is reduced if the delivery process is couched in terms of discharge source areas and sediment factors (Rieger *et al*., 1988). In this study for instance, the model representation for the major sediment delivery processes was critically reviewed and some of them were substituted.

The approaches hinted above were developed in this study in order to serve as a feedback loop between the two components of the conceptual framework. Using reservoir catchment sediment budget approach, the performances of both individual components of the framework were verified. It should be noted that in a classical or traditional modelling exercise only time series of sediment loads or concentrations data is used to calibrate and validate the model. Finally, the model is applied to predict reservoir sedimentation rate. But in the developed methodological framework both the mathematical model and sampling programme share experience and as a result it improves representation and understanding of natural dynamic systems such as watershed, and reduces uncertainties in predicting sedimentation.

3. RESULTS AND DISCUSSIONS

Although, analysis of field based data was intended for identifying erosion processes in the catchment, the subject has been addressed in almost each component of the conceptual framework. Based on the sediment flow data analysis, sheet erosion was identified as a major erosion process in the upland catchment, for instance (Ndomba *et al*., 2007). Independently, gully erosion modelling exercise found that gullies are localized erosion features in the basin (Ndomba *et al*., 2009). They contribute only 1.6% of the catchment sediment yield. Besides, SWAT model explained 56% of the variance of the daily stream sediment loads in the calibration period (Ndomba *et al*., 2008b). Furthermore, the model underestimated the measured load, according to Total Mass Criterion (TMC) by 0.9%. And the major proportion of the unexplained variance was attributed to unrepresentative measured daily mean streamflow discharges and to a lesser extent the model deficiency (Ndomba *et al*., 2008b). Besides, based on long-term SWAT model simulation, within channel sediment sources contributes 14,000 t/yr that is about 3.2% of the 1DD1-Kikuletwa subcatchment sediment yield. Since, SWAT model according to the conceptual model was meant for sediment yield modeling from sheet erosion sources, the good result achieved has independently shown that sheet erosion is a major erosion process and erosion rates are higher in agriculture land use (**Table 1**).

Table 1: The long-term spatial annual fluxes of soil loss and sediment yield from sheet erosion in the Kikuletwa subcatchments

Subbasin (HRU)	Area [Km^2]	Sediment yield (SYLD_MUSLE) [t/ha]	Soil loss (USLE) [t/ha]	Landuse	Erosion level
Weruweru	1,361	1.21	8.79	Agriculture	High
Kikafu	1,082	0.95	12.34	Agriculture	High
Mt. Meru	1,079	0.83	4.10	Agriculture	High
Sanya	1,039	0.26	2.01	Agriculture	Moderate
Upper Kikuletwa	2,674	0.08	1.19	Rangeland	Low

Besides, result of analysis of sediment flow data suggests that channel sediment sources are insignificant, especially for Kikulewa River (Ndomba *et al.*, 2007). However, there is evidence of channel bank erosion and bed erosion sources in River Ruvu. The sediment flow data in Ruvu River demonstrated higher erratic scatter between sediment loads and flow discharge than for Kikuletwa River (Ndomba *et al.*, 2007). Comparatively, probably, this indicates that Kikuletwa catchment is dominated by fewer erosion processes than Ruvu. It was therefore concluded that gully erosion is an insignificant erosion process in the area (Ndomba *et al.*, 2007).

A summary of sedimentation rates as estimated from various methods is presented in **Table 2** below. It should be noted that reservoir survey information was considered by the author as reliable method to give actual sedimentation rate. The approach adopted here is well supported by other workers such as Morris and Fan (1998). In order to check the performance of a method the relative error of estimate criterion was used. Therefore, relative errors in percent as presented in the table below in the last column, indicate the prediction performances of each sedimentation rate estimation method.

Table2: Comparison of NYM reservoir sedimentation rates as estimated by Sampling programme and sediment rating curve, “Sampling”; SWAT model simulations and sampling “Modeling”; and Reservoir survey methods.

Estimation method	Reservoir sedimentation rate (t/yr.)	Relative error (%)
Sampling	327,500	20.0
Modelling	422,000	**2.6**
Reservoir survey	411,000	

Although both methods, “Sampling” and “Modelling”, of estimating reservoir sedimentation rates seem to give acceptable results for most practical applications, the modeling approach demonstrates to be the superior method with a relative error of 2.6%. As pointed out earlier in this paper that modeling was expected to reduce linearity assumption and lumping nature of the analytical tools such as sediment rating curve used in the sampling method. Besides, it should be noted that the sampling programme did not sample the bed load and unmeasured suspended sediment load.

Therefore, the author believe that a relative error of 20% from the sampling programme encompasses many sources of errors and it is difficult to particularly single out only one. You should note that a feedback loop still exists between these two methods. For instance, the all-round hydrological year sampling programme data in year 2005 was used to establish a relative proportion between sediment loads transported major tributaries, 1DD1-Kikuletwa and 1DC1-Ruvu. And this proportion has been used in both sampling and modeling methods to estimate annual sediment loads in periods of missing flow discharges and sediment flow data for Ruvu River. Besides, both reservoir sedimentation rate estimation methods used information of sediment load released at NYM dam as derived from sampling programme. Based on the foregoing discussions this study assumed that modeling is a robust and cheap approach in estimating long term NYM reservoir sedimentation rate using sampling programme data of one hydrological year.

A sediment budget as presented in **Table 3** below for Nyumba Ya Mungu reservoir catchment has been developed by this study. It should be noted that the values presented in the table are rounded to nearest thousands for clarity purpose. The actual figures are reported in Ndomba (2007). It should be note that, one term (i.e. Sediment stored in the plains) in the table has been derived as a difference between upland catchment soil loss from sheet erosion and sediment delivered from upland sheet erosion to the channels of tributary rivers. And the latter sediment budget term is considered as a derivative of the modeling exercise.

Table 3: Summary of sediment budget for the Nyumba Ya Mungu reservoir catchment

Sediment budget Item	Mean Annual rate (t/yr.)	
	Kikuletwa	Ruvu
Upland catchment soil loss from sheet erosion	3,501,000	
Sediment stored in the plains	3.096,000	
Sediment delivered from upland sheet erosion to the channels of tributary rivers	405,000	
Within channel erosion (i.e. bed/banks) from tributary rivers	14,000	
Sediment yield rate at the outlet of main tributary rivers	419,000	**11,000**
NYM reservoir catchment sediment yield rate	**430,000**	
NYM Reservoir sedimentation rate	**411,000**	
Sediment load released from NYM reservoir	**8,000**	
Imbalance or error term	**11,000**	

Besides, an imbalance or error term is also included in **Table 3**. The error term has been determined as the difference between NYM reservoir catchment sediment yield rate and sum of NYM Reservoir sedimentation rate and sediment load released from NYM reservoir. Data from reservoir survey and sampling programme have been used to derive NYM Reservoir sedimentation rate and Sediment load released from NYM reservoir, respectively. The rest of the terms in **Table 3** have been estimated from modeling exercises.

Gully erosion contribution has been ignored in the sediment accounting, as it is insignificant compared to other figures as discussed in preceding sections. Other workers (Morris and Fan, 1998) noted that in areas with few gullies, sediment contribution by gully erosion might be small enough to be ignored. As reported by Ndomba (2007) basing on SWAT model simulations that proportion of eroded sediment from sheet erosion that reaches the main channels is between 7 and 20%. If one had adopted these values as sediment delivery ratios from gully erosion, probably this might suggest that actual gully erosion contribution to catchment sediment yield is lower. And, therefore, the discussion above suggests that omission of gully erosion item in the sediment budget has been done with confidence. Probably, one would note that a feedback loop between modeling components does exist. One would also note that corresponding values for 1DC1-Ruvu subcatchment for some sediment budget items are missing. This study could not establish them. Issues such as data availability hindered in-depth representation of this subcatchment (Ndomba *et al*., 2008b). Besides, NYM intervening catchment sediment yield contribution has been ignored on the basis of analysis and field observations.

Besides the author would like to note that the actual sedimentation rate as determined in this study and presented in **Table 3** has uncertainty. As reported in literature, all techniques for estimating reservoir volume incorporate errors (Morris and Fan, 1998). An estimated error of about ±10% to 30% in determining reservoir capacity volumes have been reported in Morris and Fan (1998) by various workers. Errors of only a few percent in the total volume estimate can produce errors of several tens of percent in the computed sedimentation rate (Morris and Fan, 1998). This indicates that the computation of sedimentation rate extremely sensitive to small errors in volume estimates, especially when the volume changes are relatively small because of a short intersurvey period or low sedimentation rate (Morris and Fan, 1998). And the foregoing discussions suggest that the imbalance or error tem in **Table 3** above could be incorporated into uncertainty in determining actual reservoir sedimentation rate.

It was hypothesized that sheet erosion, gully erosion and channel bed/banks erosion to be the most dominant erosion processes in the basin. This study by using the conceptual framework has revealed three main processes; namely sheet erosion, gully erosion and channel bed degradation/aggradations. However, the sheet erosion has been found to dominate and it contributes more than 90% of sediments to downstream NYM reservoir. The presence of other processes in the catchment though small suggests that the method adopted was so versatile to simulate all possible erosion processes in NYM reservoir catchment and the hypothesis was met.

The result from the analysis of field data was not only used to identify erosion processes and sediment sources but they were further used to guide modeling activities such as model setup, calibration and verification. For instance, as a result of initiating the suspended sediment sampling in Ruvu River at 1DC1 station, the results from well-monitored gauging station, the Kikuletwa at 1DD1 was extrapolated to this gauging station. Also the sampling programme enabled the understanding of the differences that exist in hydrological responses of the two neighbouring subcatchments, 1DD1 and 1DC1. The influence of swamps and upstream natural Lakes such as Jipe to the sediment transport has been understood (Ndomba *et al*., 2007). The modeling activities confirmed the processes identified by sampling data alone. However, the modeling activities have improved much on identification of location based sediment sources.

Causes of gully erosion and estimation of its contribution to the catchment sediment yield has been studied using readily available environmental variables. The results have been verified and it has concluded that the unexplained variance of the observed gully densities mostly could be due to poor resolution of some spatial data used and not otherwise (Ndomba *et al*., 2009).

Sediment yield modeling at subcatchment levels using MUSLE as implemented in SWAT model eliminated the use of delivery ratio. The resulting subcatchment sediments yields were routed through the main channel using simplified Bagnold's equation. Therefore, sediment yield from sheet erosion has not been factored. However, sediment delivery ratios were used to estimate sediment yield from gully erosion. It could be learned from gully erosion modelling exercise that even if the delivery ratio had not been applied the gross contribution from gully erosion would have been 3.2%. Since, sheet erosion contributes more than 90% of sediments load delivered to catchment outlet therefore; one would note that the uncertainty involved in estimating sediment delivery ratio has been substantially reduced.

4. CONCLUSIONS AND RECOMMENDATIONS

Generally, the study has come up with a number of output and major scientific contributions in the area of sedimentation modelling studies. The major erosion processes in the catchment is sheet erosion from agricultural fields in the headwater regions of Pangani River Basin. Sheet erosion contributes more than 90% to the Nyumba Ya Mungu reservoir sedimentation. Based on long-term SWAT model simulation, within channel sediment sources contributes about 3.2% of the 1DD1-Kikuletwa subcatchment sediment yield. Besides, gully erosion contribution to the total sediment yield in the NYM reservoir catchment was estimated to be only 1.6%.

Moreover, the study found out that the erosion rates from sheet erosion are high and above the recommended standards for sustainability of agricultural activities. Major sediment source areas include Weruweru and Kikafu catchments on the foot slopes of Mount Kilimanjaro and catchments in the Mount Meru foot slope.

Generally, 1DD1-Kikuletwa catchment contributes about 97.5% of the total sediment inflow to Nyumba Ya Mungu reservoir. Therefore, 1DC1-Ruvu catchment contributes only 2.5% of the total inflowing sediment load to the reservoir. The study has also found out that currently most of the sediments eroded from hill slopes don't find their way to the reservoir because they are deposited in the plains which have been estimated to cover about 73% of the catchment area.

Sedimentation rate at Nyumba Ya Mungu reservoir is 411,000 t/yr. A total of 13 Mm^3 of sediments has been trapped and deposited into the reservoir bed since it was commissioned in year 1968. Only 1.0% of total storage has been depleted. The dead storage has been depleted by 4.4%. The study has found that the deposited sediments are progressively moving towards the dam. And it was observed that the trapped sediments are mostly deposited in the original main channel within 25 km from the dam axis. The study has also estimated that the reservoir can still be operated economically and safely for at least another 100 years from 2005 with little interference from sedimentation problems under the present condition of landuse. However, the author would like to note that the low sedimentation rate as determined from this study could be attributed to large size coverage of plains and therefore sedimentation rate in other reservoirs in the country or elsewhere might be higher depending on the morphological characteristics of respective reservoir catchments.
The author would like to point out that this study does not close the chapter of sedimentation modelling. Some issues which limited the study undertaking in one way or another are proposed for further work.

- *Estimating delivery ratio and understanding the gully erosion processes*. Even though the sediment delivery concept is old, still uncertainty exists in estimating the delivery ratios. Besides, gully erosion processes are still not well understood and their reported contributions to sediment yields from literature differ widely.
- *Study of sediment transport dynamics of the deposited sediments in the plains*. This study revealed that plains in the catchment behave as major sediment depository sites and only a few proportions finds its way to the reservoir downstream. This actually calls for a further research work to study the dynamics of the sediment transport of the deposited sediments in the plains, and probably what will happen 100 years from now.
- *Testing the developed conceptual framework to other gauged catchments*.

  The methodological framework adopted in this study has helped to better understand the erosion processes and reservoir sedimentation in the Pangani River Basin, but as a model in the making, it needs to be tested widely before being used for operational purposes.

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