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Developing Sediment Yield Prediction Equations for Small Catchments in Tanzania

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1. Introduction

Sediment yield refers to the amount of sediment exported by a basin over a period of time, which is also the amount which will enter a reservoir or pond located at the downstream limit of the basin (Morris and Fan, 1998). Estimate of long-term sediment yield have been used for many decades to size the sediment storage pool and estimate reservoir life. However, these estimates are often inaccurate especially for small catchments. Besides, it is known from literature that long term period sampling programmes are required to capture the high variability of sediment fluxes in these catchments (Horowitz, 2004; Thodsen *et al*., 2004). The correlation of sediment yields to erosion is complicated by problem of determining the sediment delivery ratio, which makes it difficult to estimate the sediment load entering a reservoir/pond on the basis of erosion rate within the catchment (Morris and Fan, 1998). Sediment yield from the dam catchment is one of the parameters controlling sedimentation of small dams. This has to be estimated if future sedimentation rates in a dam are to be predicted.

Non Governmental Organizations (NGOs) and Government Agencies (GAs) have constructed thousands of small dams in semi-arid regions of East and Southern Africa including Tanzania to provide water for livestock and small-scale irrigation (Lawrence *et al*, 2004; Faraji, 1995). In Tanzania, in particular, at present it is not known whether the original storage capacities of these dams still exist as a result of many years of operations. Besides, irrigation/water supply schemes ponds/reservoirs are normally draining small catchments. Most of the small catchments are characterized as ungauged. The effective life of many of these dams is reduced by excessive siltation – some small dams silt up after only 2 years. This issue is poorly covered in the many small dam design manuals that are available, which mostly focus on civil engineering design and construction aspects. While a capability to estimate future siltation is needed to ensure that dams are sized correctly, and are not constructed in catchments with very high sediment yields, little guidance is available to small dam planners and designers (Lawrence *et al*, 2004). Therefore, prediction of sediment yields from catchments is very important where water resources sedimentation is a serious problem like Tanzania and construction of dams is needed (Mulengera, 2008).

This chapter discusses also the findings of a few previous representative and related research works in Tanzania and the region at large as this study is a follow up research. These studies were selected in order to cover a wide range of study methods.

Christiansson (1981) made detailed recording of the soil erosion complex within five selected catchments in Dodoma, the semi-arid savannah areas of central Tanzania, 4 of which with reservoirs (Fig. 2.1). The principal methods employed include field surveying and air photo interpretation. The main approach was physical geographical aiming at studying the existing features of soil erosion and sedimentation and analysis of the underlying causes of the processes. Christiansson (1981) estimated sediment yields of 260 – 900 $t/km^2/yr$ or 2.6 – 9 t/ha/yr as averages for the longest periods of available records. Although, Christiansson asserted that the estimated sediment yields from his study were of the same order of magnitude as those recorded in similar environments in other parts of East Africa, the scope of the study was limited in-terms of spatial and climate representation.

Mulengera and Payton (1999) in their review of the soil loss estimation equations noted that most of the countries in the tropics have no appropriate and accurate soil erosion prediction equations, although the Soil Loss Estimation Model for Southern Africa (SLEMSA) and the Universal Soil Loss Equation (USLE) are used in different tropical countries. The SLEMSA(developed in Zimbabwe) 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 and Payton,1999). The USLE (developed in the USA) and widely used throughout the world has in most cases been found to be inapplicable in the tropics. This is due to the fact that the equation's soil erodibility nomograph commonly gives unrealistic values for tropical soils. Although derivation of the erodibility equations for the tropical soils have shown that soil erodibility is strongly related to texture-related soil characteristics as has been shown for soils in temperate regions, there are differences in the magnitudes of the characteristics for soils with relatively similar erodibility values in both regions (Mulengera and Payton, 1999). This is due to differences in clay, silt, and sand fractions of the soils and possibly rainfall characteristics found in the two regions. While soils in the temperate region have all the three fractions well distributed, soils in the tropics are mainly composed of clay and (or) sand fractions with a relatively small fraction of silt content (Mulengera and Payton, 1999). So Mulengera and Payton concluded that it is impossible to develop one universal soil erodibility equation. Therefore, the prediction of soil erosion in the tropics using the USLE or its revised version (RUSLE), had been hampered by the common inapplicability of the soil erodibilty nomograph for tropical soils. Furthermore, the table values developed in the U.S.A. for estimating the crop and soil management factor of the equation are not applicable for farming practices and conditions found in the tropics (Mulengera and Payton, 1999). However, some recent studies have shown that it can give good results, especially, when its recent version, the Modified Universal Soil Loss Equation (MUSLE) is used (Ndomba, 2007).

Mulengera and Payton (1999) presented an equation for estimating the USLE -Soil erodibility factor, which resulted from a wider research programme initiated to identify a suitable soil loss prediction equation for use under Tanzanian conditions. The derived equation based on soil texture-related parameters which is technically accurate (i.e. explaining about 84 % of the erodibility variations) for estimating the erodibility factor of the (R)USLE in the tropics for soils whose physical and chemical characteristics are similar to the soils used in the derivation. The equation is useful for soil conservation planning in these areas currently suffering from severe soil erosion (Mulengera and Payton, 1999). The equation was successfully used by Mtalo and Ndomba (2002) in Pangani basin, in the North-eastern part of Tanzania.

Mtalo and Ndomba (2002) have reported alarming high rate of soil erosion of up to 2,400 $t/km^2/yr$ or 24 t/ha-yr in the upstream of Pangani river basin covering parts of Arusha, Kilimanjaro and Tanga regions (Fig. 2.1). Mtalo and Ndomba used USLE equation to map and estimate on site potential soil loss. In the basin high erosion rates can be measured in different perspectives such as increased agricultural and other human activities. For instance, in Arumeru district, which is one of the districts in the Arusha region, soil erosion is one of the major obstacles to increasing or sustaining the agriculture production. The whole district is affected by soil erosion, but the reasons differ from place to place. The amount of livestock in the district is considered to be far above the carrying capacity of the present land area devoted to grazing. Agricultural activities are a contributing factor to increased soil erosion rates in the Pangani basin upstream of Nyumba Ya Mungu reservoir (Mtalo and Ndomba, 2002).

Of recent, there have been attempts to apply complex distributed, physics-based sediment yield models such as Soil and Water Assessment Tool (SWAT) for poor data large catchments, Kagera, Simiyu and upstream part of Pangani River catchment, in Kagera, Mwanza and Arusha/Kilimanjaro regions, respectively, in Tanzania. SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) to estimate sediment yield (Arnold *et al.*, 1995). The model operates at daily time step with output frequency of up to month/annual. However, in order to adopt the model for general applications in watershed management studies, researchers recommended for SWAT model improvements (Ndomba *et al.*, 2005; Ndomba *et al.*, 2008).

One would note that most of the previous sediment yield estimates studies in Tanzania and the region at large were catchment specific. The results could not be transferred easily to other hydrologic similar catchments (Rapp *et al.*, 1972; Mulengera and Payton, 1999; Mulengera, 2008; Ndomba, 2007, 2010). In order to estimate catchment yield researchers were forced to use uncertain factor such as sediment delivery ratio (Ndomba *et al.*, 2009). In some studies attempts were made to develop only a simple procedure which would distinguish between dams that will silt up rapidly from dams that will have a sedimentation lifetime well in excess of twenty years (Lawrence *et al*, 2004). The estimation tools used were either complex for operational and wider application or data intensive (Ndomba *et al*. 2008). In some cases due to limitation in data the developed Sediment yield predictive tools could not be validated (Rapp *et al.*, 1972; Lawrence *et al*, 2004). As acknowledged by Faraji (1995) and others, at present, there is very scanty knowledge about reservoir sedimentation in Tanzania. Previous studies were done on few reservoirs/dams. The studies gave some guidelines on the rate of sedimentation of the respective areas (Rapp *et al.*, 1972). However, this knowledge should be backed with further extensive surveys and resurveys to get improved relationships. Critical tools in this context include sediment yield and/or reservoir life estimation. The country has limited resources in terms of funding and human capital for developing the planning tools (Mulengera, 2008). The latter problem might be common to most of the developing countries.

Based on the discussions above and literature, generally, sediment yield models may vary greatly in complexity from simple regression relationships linking annual sediment yields to climatic physiographic variable such as regional regression relationships to complex distributed simulation model (Garde and Ranga Raju, 2000). Modelling as one of the approaches for estimating catchment sediment yields, if properly applied, can provide information on both the type of erosion and its spatial distribution across the catchment. Sediment mobilized by sheet and rill erosion may be deposited by a variety of mechanisms prior to reaching stream channels. Six major factors which influence the long-term sediment yields/delivery from a catchment based on Renfro (1975) as reported in Morris and Fan (1998) and critically reviewed by Ndomba (2007) are: i) Erosion process - the sediment delivered to the catchment outlet will generally be higher for sediment derived from channel-type erosion which immediately places sediment into the main channels of the transport system, as compared to sheet erosion; ii) Proximity to catchment outlet - sediment delivery will be influenced by the geographic distribution of sediment sources within the catchment and their relationship to depositional areas. Sediment is more likely to be exported from a source area near the catchment outlet as compared to a distant sediment source, since sediment from the distant sources will typically encounter more opportunities for re-deposition before reaching the catchment outlet; iii) Drainage efficiency- hydraulically efficient channels networks with a high drainage density will be more efficient in exporting sediment as compared to catchments having low channel density; iv) Soil and land cover characteristics - finer particles tend to be transported with greater facility than coarse particles. Because of the formation of particle aggregates by clays, silts tend to be more erosive and produce higher delivery ratios than clay soils; v) Depositional features - the presence of depositional areas, including vegetation, ponds, wetlands, reservoirs and floodplains, will decrease the sediment yields at the catchment outlet. Most eroded sediments from large catchments may be re-deposited at the base of slopes, as outwash fans below gullies, in channels or on floodplains; vi) catchment size and slope - a large, gently sloping catchment will characteristically have a lower delivery ratio than a smaller and steeper catchment.

This chapter is therefore reporting the developed sediment yield-fill equations as categorized as regional regression relationships for various climatic regions in Tanzania as simple and efficient planning tools of water supply schemes small reservoirs/pond with limited data. In this study additional new data on dams is used. It should be noted that requirements for data and computational modelling skills rule out the use of more sophisticated methods to predict sediment yields, and as a result a simple regional sediment yield predictor was chosen for this application. The equations are developed from readily available data on catchment area and reservoir sediment fill from Ministries and Government Agencies. The size of the area is very important factor in respect to the total yield of sediment from a catchment. However, it should be noted that its relative importance to the influence of the sediment delivery ratio and sediment production rate is subject to questioning. It is suggested in the literature that sediment production rates declined with increasing catchment area (Morris and Fan, 1998). This theory is supported by the fact that the probability of entrapment and lodgment of a particle being transported downstream increases as the drainage area increases. Besides, for the same length of a river network, the smaller the catchment area the higher the drainage density as well the sediment yields. The proximity to the catchment outlet may also be indirectly related to catchment size. The preceding discussions suggest that catchment area size may sometimes be directly or indirectly linked to various factors controlling sediment delivery to the outlet of the catchment. However, catchment area size could not be directly related to erosion process, soil type and land cover. Such limitations would render the general relationships between catchment area size as independent variable and the sediment yield-fill be used only for preliminary planning purposes or as a rough check. It is anticipated that small dam designers/planners would be able to use these tools /methods; they typically need to carry out assessments rapidly using limited local data, and may not have software skills or access to computers.

2. Materials and methods

2.1 Description of the study area

The study area, Tanzania, is situated in East Africa just south of the equator (Fig. 2.1). Tanzania lies between the area of the great Lakes—Victoria, Tanganyika, and Nyasa—and the Indian Ocean. It contains a total area of 945,087 km², including 59,050 km² of inland water (Fig. 2.1). It is bounded on the North by Uganda and Kenya, on the East by the Indian Ocean, on the South by Mozambique and Malawi, on the South West by Zambia, and on the West by Democratic Republic of Congo, Burundi, and Rwanda, with a total boundary length of 4,826 km, of which 1,424 km is coastline.

Tanzania has a tropical climate with 3 major climatic zones (Fig. 2.2) viz. dry, moderate and wet. Moderate Climatic zone occupies a large area of Tanzania (URT, 1999). It receives rainfall for 1 to 3 months in a year. The administrative regions which fall under this climatic zone are Tabora, Mwanza, Mara, Iringa, Morogoro, Arusha, Tanga, Moshi, Lindi and Bukoba. In the highlands, temperatures range between 10 and 20 °C (50 and 68 °F) during cold and hot seasons, respectively. The rest of the country has temperatures rarely falling lower than 20 °C (68 °F). The hottest period extends between November and February (25 – 31 °C) while the coldest period occurs between May and August (15 – 20 °C). Tanzania has two major rainfall regions. One is unimodal (December - April) and the other is bimodal (October - December and March - May). The former is experienced in southern, south-west, central and western parts of the country, and the latter is found to the north and northern coast. In the bimodal regime the March - May rains are referred to as the long rains or “Masika”, whereas the October - December rains are generally known as short rains or “Vuli”.

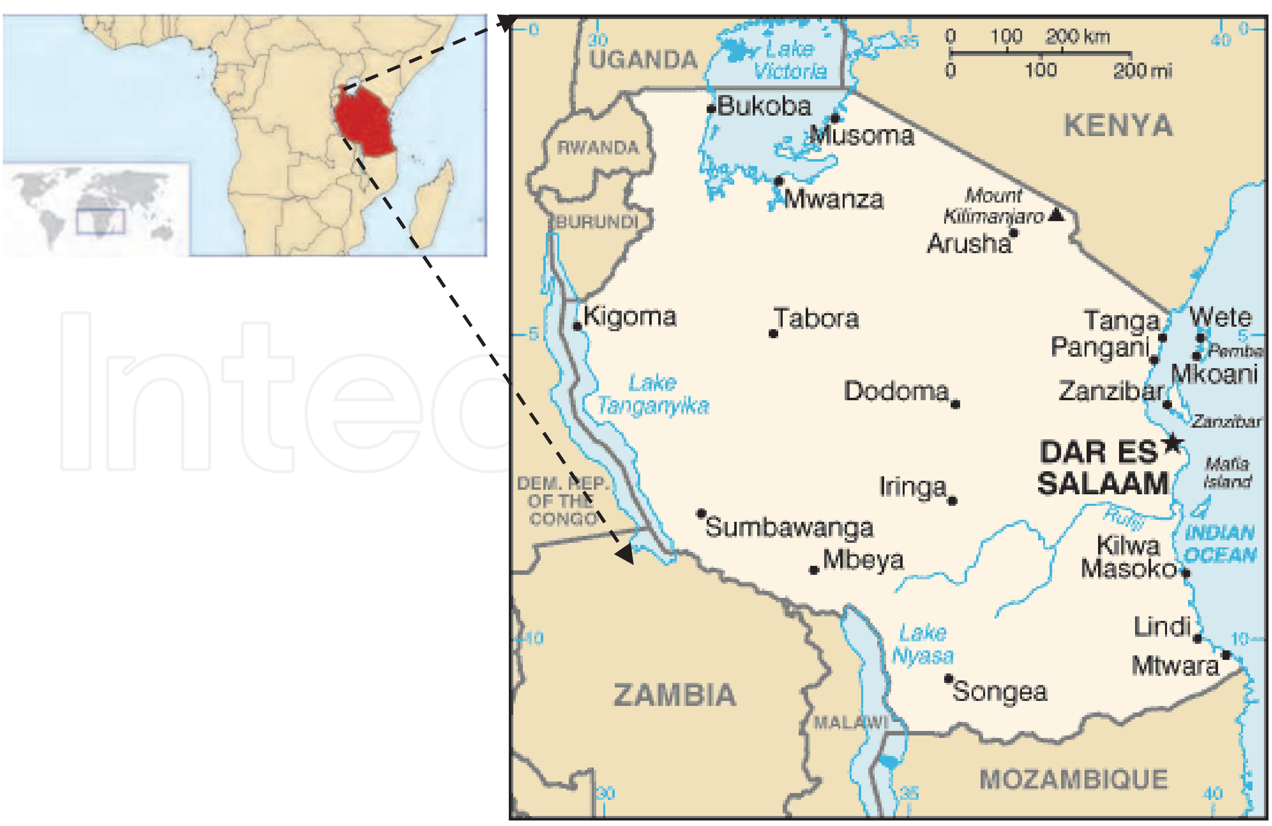

Fig. 2.1. Location map of Tanzania

Fig. 2.2. Map showing Climatic zones of Tanzania (as adopted from URT, 1999)

According to PLDPT (1984) Tanzanian soils are very varied, a simplified classification follows: a) Volcanic soils: are of high agricultural potential and livestock production tends to be restricted to zero-grazing systems. They predominate in Arusha, Kilimanjaro and South west Highlands, Kitulo plateau. At high and medium altitudes they are notable for the production of forage for dairy production; b) Light sandy soils: predominate in the coastal areas. Grazing is available during the rains but the soils dry out rapidly thereafter and the forage has little worth; c) Soils of granite/gneiss origin: are poor and occur mainly in mid-west especially in Mwanza and Tabora; d) Red soils: occupy most of central plateau. They produce good grazing in the limited rainy seasons and the quality of herbage persists into the dry seasons; e) Ironstone soils: found in the far west, mainly in Kagera, Kigoma and Sumbawanga. They are poor and acidic but can be productive with inputs, *i.e.*, mulching and manuring; and f) The mbuga black vertisols are widespread and an important source of dry season grazing.

The following are the descriptions of the respective regions from which the dam data for this study were collected. These are Dodoma, Shinyanga, Singida, Tabora, and Arusha (Tables 2.2.1 & 2.2.2).

Serial No.	Names Of dams	Catchment Area (km^2)	Full Supply Level, FSL,(m)	Capacity at FSL (Million m^3)	Year of Construction	Sed Fill (m^3)	Year(Data Collected)	Sed Fill rate (m^3 Per Year)
Dodoma region								
1	Mambali	2.7	*NA*		1958	21500	1978	1075
2	Mabisilo	25	*NA*		1956	31500	1978	1431.8
3	Kakola	3.7	*NA*	0.202	1954	19700	1978	820.8
4	Manolea	3	*NA*	0.033	1956	15400	1978	700
5	Kasisi	3.2	*NA*	0.02	1968	7300	1978	730
6	Mbola	6.4	*NA*	0.016	1972	7500	1978	1250
7	Igingwa	10	*NA*	0.20	1958	2800	1978	1400
8	Matumbuhi	16.8	59.74	0.31	1960		1978	1322.4
9	Buigiri	10.3	35.26	0.48	1969		1978	1410
10	Imagi	2.2	*NA*	0.1695	1934		1971	950
11	Matumbulu	15	*NA*	0.333	1949		1962-74	1374.5
12	Msalatu	8.5	*NA*	0.42	1944		1974	1225.8
13	Kisongo	9.3	*NA*	0.1265			1969-71	1228
Shinyanga region								
14	Bubiki	11	2.75	0.35				1584
15	Ibadakuli	10	4.9	0.37				1472
16	Malya	15	5.8	1.49				2011
17	Nguliati	12	3.35	0.49				1593
18	Sakwe	9	3.65	0.28				1357.4

Note: "NA" and "blank" imply No Any data.

Table 2.2.1. Sedimentation data of small dams in Dry climatic zone for regions of Dodoma and Shinyanga

Dodoma region is characterized by long dry seasons (April to December) and short rainy seasons (December to March). Mean annual rainfall in the area range from 500 to 600 mm/annum and potential evaporation ranges between 2000 to 2500 mm per annum (Christiansson, 1981). The topography of the central semi arid Tanzania is characterized by plains and scattered inselberg or ridge. The soils appear in catena sequence where the upper slopes of inselberg have thin stony soils. The valley bottoms and flood plains have black and grey deposits. Natural vegetation of dense thicket or "miombo" woodland has generally been replaced by semi natural vegetation of grasses and herbs. The inhabitant of the study area are cultivating pastoralist. They mainly practice shifting cultivation where no manure is applied. They maintain large heards of cattle, sheep, and goats. The staple crops grown are sorghum and bulrush millet, maize also grown on significant areas.

Tabora region								
Serial No.	**Names of Dams**	**Cat Area (km^2)**	**Full Supply Level (m)**	**Capacity At FSL (Million m^3)**	**Year of Construction**	**Year (Data Collected)**	**Sed Fill (m^3)**	**Sed Fill rate (m^3 Per Year)**
1	Malolo	15	35.7	0.936	1962	1975	19300	1485
2	Itambo	25	29.3	0.234	1947	1978	96200	3103
3	Magulya	15.8	35	*NA*	1957	1978	35200	1676
4	Ulaya	8.3	30.8	0.298	1947	1978	31600	1019
5	Igurubi	1.2	26.7	0.113	1959	1978	20900	1100
6	Charo	6.7	28.5	0.015	1969	1978	11700	1300
7	Kakolo	3.7	33.8	0.202	1954	1978	19700	820
8	Manolea	3	30.6	0.033	1956	1978	15400	700
9	Kasisi	3.2	13.2	0.02	1968	1978	7300	730
10	Mbola	6.4	31.8	0.016	1972	1978	7500	1250
11	Usoke Mission	1.9	28.2	0.02	1971	1978	3150	450
12	Kalangali	2.8	1200.7	0.84	1958	1978	88400	4420
13	Uchama	11	36.9	1.322	1955	1978	27700	1204.3
14	Mambali	2.7	24.9	*NA*	1956	1978	21500	977.3
15	Mabisilo	25	35.0	*NA*	1956	1978	31500	1431.8
16	Nkinazawa	180	29.6	0.75	1956	1978	110000	5000
17	Iduduma	267	32.9	0.86	1959	1978	140000	7368
18	Mwamashimba	16.5	25.0	*NA*	1973	1978	21500	4300
19	Bulenya Hills	194	36	1.62	1961	1978	96400	5670.5
20	Sorefu	7.5	28.1	0.045	1970	1978	9400	1175
21	Urambo	38	18.2	*NA*	1956	1978	75717	3441.7
22	Tura	105	30.8	0.27	1948	1978	108003	3600
23	Utatya	4	*NA*	35.4	1959	1978	11050	581.6
24	Igingwa	10	26.2	0.2	1958	1978	28000	1400
Arusha region								
25	Moita Bwawani	97		1.556				31120
26	Moita Kiloriti	115		1.257				37710

Serial No.	Names of Dams	Cat Area (km²)	Full Supply Level (m)	Capacity At FSL (Million m³)	Year of Construction	Year (Data Collected)	Sed Fill (m³)	Sed Fill rate (m³ Per Year)
27	Leken	183		6.972				223104
28	Kimokouwa	110		0.950				40850
29	Lossimingori	94		1.640				57400
30	Moriatata	120		1.342				34892
31	Losirwa	65		0.670				20783.95
32	Ngamuriak	76		1.104				18768
33	Bashay	78		1.420				8520
34	Meserani	56		0.568				17608
35	Lepurko	87		0.856				24837.05

Table 2.2.2. Sedimentation data of small dams in Moderate climatic zone for regions of Tabora and Arusha

Shinyanga region is characterized by a tropical type of climate with clearly distinguished rainy and long dry seasons. According to meteorological statistics the average temperature for the region is about 28°C. The region experiences rainfall of 600 mm as minimum and 900 mm as maximum per year. The rainy season usually starts between mid-October and December and ends in the second week of May. Normally it has two peak seasons. The first peak occurs between mid- October and December, while the second one, the longer season, falls between February and mid-May. As such, the whole rainy season covers a total of almost 6 months, with a dry spell which usually occurs in January. The dry season begins in mid-May and ends in mid-October. This is a period of about 5 months. The dry season is the worst period for the Shinyanga region. The topography of Shinyanga region is characterized by flat, gently undulating plains covered with low sparse vegetation. The North-Western and North- Eastern parts of the region are covered by natural forests which are mainly "miombo" woodland. The Eastern part of the region is dominated by heavy black clay soils with areas of red loam and sandy soil. It is observed that most of the Shinyanga region is dry flat lowland. Thus its agro-economic zones are not well pronounced as it is with some regions in the country. The soils are hard to cultivate, pastures become very poor, and availability of water for domestic use and livestock become acute. The amount and distribution pattern of rainfall in the region is generally unequal and unpredictable. This implies that rainfall as a source of water for domestic and production purposes in the region is less reliable for sustainable water supply. Despite of the recent mushrooming of mine industry, agriculture has continued to dominate the livelihood and economic performance of Shinyanga region. The sector contributes about 75 percent to the regional economy and employs about 90 percent of the working population in the region. Agriculture is dominated by peasantry farming. Main cash crops are cotton and tobacco while the main food crops are maize, sorghum, paddy, sweet potatoes, millet and cassava. The region has the largest planted area of maize and second largest for paddy and sorghum than other regions in

Tanzania. Besides farming, livestock keeping is also a major activity in the region. Cattle, goats and sheep are the major domesticated animals. Modern diary farming and poultry keeping are confined to urban centers

Tabora region is among the areas of Tanzania which are in moderate climatic zones. Tabora region is located in the mid-western part of Mainland Tanzania. Tabora is characterized as tropical type of climate with clearly distinguished rainy and dry seasons. According to meteorological statistics the average temperature for the region is about 27^{0}C. Tabora receives Mean Annual Rainfall of 892 mm/annum or 74 mm/month. In Tabora, about 76% of the population are farmers, and thus agriculture is the largest single sector in the economy directory producing about 80 percent of Tabora region's wealth of goods and services. Main cash crops grown are tobacco, cotton and paddy. Tobacco and cotton are mainly grown for export markets. Principal food crops are maize, sorghum, cassava, sweet potatoes and legumes.

Arusha region lies in moderate climatic zone. With the exception of a few spots the region is in the high altitudes ranging from 800 to 4,500 meters above sea level. Because of the high altitude the region experiences moderate temperatures with rainfall varying with the altitude. The average annual temperature is 21^{0}C in the highlands and 24^{0}C in the low lands. Arusha region has two types of rainfall patterns: unimodal and bimodal. The southern district of Karatu normally enjoys unimodal rainfall which usually starts in November and ends in April. The rainfall in this district is usually reliable, ranging from 800 to 1,000 mm/annum. The major crop produced is cereals. Soils have been classified by colour into grey, brown and red brown. The extensive soils which originate from recent volcanic ash are found to the north-western parts of the region, west of the rift valley and in the Ngorongoro massif. Brown soils cover large areas in the central part and western side of the region. The southern- eastern areas are characterised by grey brown and red-brown soils. Soil erosion is particularly severe in the heavily settled central part of the region. Generally soil erosion is widespread throughout the region and is deemed to be an environmental disaster in the making.

2.2 Data type and sources

This study collected readily available secondary data from reports of Ministry of Water and Irrigation (Husebye and Torblaa, 1995) as adopted in Tables 2.2.1 & 2.2.2. However, data from Arusha in Table 2.2.2 were sourced from a recent study by Malisa (2007). They include name of the dam, full supply level of the dam, capacity of the dam at full supply level, year of construction, accumulated sediment volume in the dam (Sed Fill), dam survey Year (Year Data Collected), volumetric rate of sediment accumulation in the dam (Sed Fill per Year), catchment area, and Sediment yield. It should be noted also that important data such as geographical locations of these dams are missing. The dams were built for various purposes, including and not limited to irrigation, domestic water supply, livestock watering, flood control and fishing.

It should be noted that most of these sedimentation data presented in Tables 2.2.1 and 2.2.2 were collected using mainly two approaches, namely, direct measurement of transported materials (*i.e.*, suspended sediment concentration) and measurement of the rate of siltation of reservoirs/dams. The author would like to note that the first procedure has some setbacks, especially, when practiced in tropics. For instance, a majority of sediment would be transported in one or two days. Typically for Tanzania, most of sediment samples had been taken at medium or low stage. The high stages were hardly sampled. This might have made it difficult to establish a linear relationship between sediment load and river discharge. Surveys of reservoirs/dams whose relevant technical maps were available were done. Profiles available from old/design maps were compared with the new sounding.

2.3 Data analysis

Although the data collected are scarce (*i.e.*, only 53 dams) but one could see that based on climatic zonation about seventy percent (70%) of Tanzania land is represented. Besides, the data coverage represents a wide range of dam and catchment physical characteristics viz. catchment area 1 - 267 km^2; dam capacity at FSL, 0.02 - 35 Million m^3 (Table 2.3). The mean values are 41.7 km^2 and 1.5 Million m^3 for catchment area and dam capacity, respectively. Notwithstanding the high spatial variability of data as captured by high Coefficient of variation (Cv), the data represent the population as demonstrated by low Standard Error of the Mean (SEM).

Serial No.	Statistics	Catchment area (km^2)	Dam capacity at Full Supply Level (Million m^3)
1.	Lowest	1.20	0.02
2.	Maximum	267.00	35.40
3.	Mean	41.66	1.52
4.	Standard Deviation (STD)	59.62	6.41
5.	Coefficient of Variation, Cv (%)	143.12	422.76
6.	Standard Error of the Mean, SEM	8.19	1.17

Table 2.3. Summary statistics of catchment size and dam capacity of data used in this study

2.4 Development of sediment yield-fill equations

Sediment yield-fill equations were developed by regression analysis approach. It should be noted that if data on sediment yield-fill and catchment characteristics are available from many sites, it may be possible to develop a regression relationship which describes the sediment yield within the region as a function of independent variables such as catchment area, slope, land use, and rainfall erosivity (Morris and Fan, 1998). The only independent variable used for this study is the catchment area as it was readily available. This study assumed the following: i) the sample is representative of the population for the inference prediction; ii) the error is a random variable with a mean of zero conditional on the explanatory variables; iii) the independent variables based on low standard error of the mean (SEM) as presented in Table 2.3 were measured with no error; iv) the predictors are linearly independent, *i.e.* it is not possible to express any predictor as a linear combination of the others; v) the errors are uncorrelated, that is, the variance-covariance matrix of the errors is diagonal and each non-zero element is the variance of the error; and vi) the variance of the error is constant across observations (homoscedasticity). These are sufficient conditions for the least-squares estimator to possess desirable properties, in particular, these assumptions imply that the parameter estimates will be unbiased, consistent, and efficient in the class of linear unbiased estimators. Besides, sediment yield is assumed as equal to sediment fill due to the uncertainty involved in estimating trap efficiency of small dams in the study area. It should be noted that previous researchers such as Mulengera (2008) adopted a similar approach. However, the author is aware that the actual data rarely satisfies the assumptions. That is, the method is used even though at some points the assumptions are not necessarily true.

Firstly, the analysis was conducted to choose type of regression equation forms. Two candidate's forms of equations were investigated, which are straight line and power function (Equations 2.4.1 & 2.4.2). This was achieved by comparing the strength of correlation between sediment fill and catchment area, and corresponding log-transformed values (2.4.3). A power relationship is confirmed when the correlation of log-transformed is high, otherwise, a linear model is chosen.

$$y_i = \beta_o + \beta_1 x_i + \varepsilon_i \text{, i = 1, …, n.} \tag{2.4.1}$$

Where n is a number of observations, x_i, is independent variable (catchment area), y_i, dependent variable (Sediment yield-fill), and two parameters, β_0 and β_1, and ε_i is an error term and the subscript i indexes a particular observation.

$$y_i = \alpha\, x_i^{\beta} \tag{2.4.2}$$

where a and β are coefficient and exponent of the equation, respectively, y_i and x_i are as defined above.

$$\text{Log } y_i = \text{Log } \alpha + \beta \text{ Log } X_i \tag{2.4.3}$$

Secondly, the parameter values were estimated under Excel 2007's Regression Analysis Tool using 70% of the data set, where applicable. The splitting of data was possible for cases where the sample size was adequate for 2 independent variables (*i.e.*, α, β) as presented above. As recommended by Statsoft (2011) at least 10 to 20 times as many observations (cases, respondents) as variables, should be used for stable estimates of the regression line and replicability of the results. The tool outputs, among others; the t statistic (a measure of how extreme a statistical estimate is); a p-value (a measure of how much evidence we have against the null hypothesis, Ho, no change or no effect; confidence interval (an interval in which a measurement or trial falls corresponding to a given probability, the best confidence interval used is 95%); degrees of freedom (the minimal number of values which should be specified to determine all the data points), *df*; the standardized residual value (observed minus predicted divided by the square root of the residual mean square), Coefficient of determination, R^2 (this is the square of the product-moment correlation between two variables -It expresses the amount of common variation between the two variables); Multiple R (is the positive square root of R-square - this statistic is useful in multivariate regression when you want to describe the relationship between the variables); The standard error (is the standard deviation of a mean). The developed equations were validated using independent data set (30%), where appropriate.

3. Results and discussions

3.1 Selected regression model

As a result of conducting correlation analysis as described under section 2.4 above and qualitative analysis of scatter plots (Figs. 3.1a,b) below, the power function was chosen as the best regression model for this study. It can be seen from the plots that the strength of correlation increases substantially with log-transformation of selected data set, *i.e.*, from R^2 equal to 0.037 to 0.665.

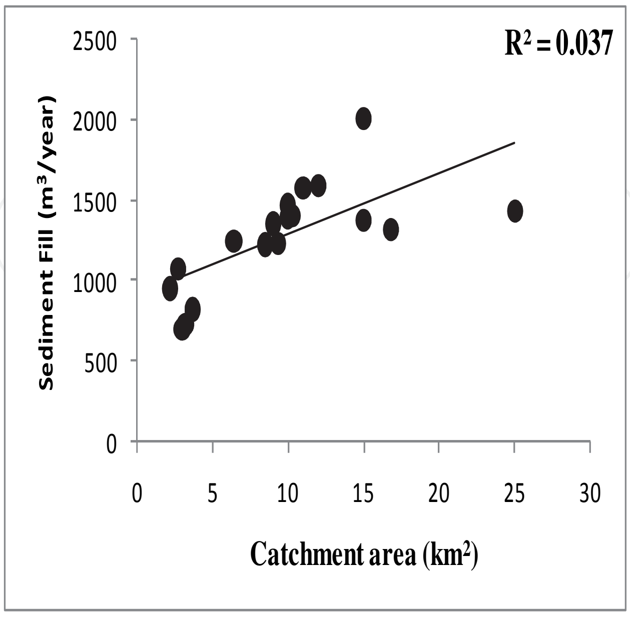

Fig. 3.1. (a) Scatter diagram of Sediment Yield-Fill in m^3/year against catchment area in km^2 for dry climatic zone.

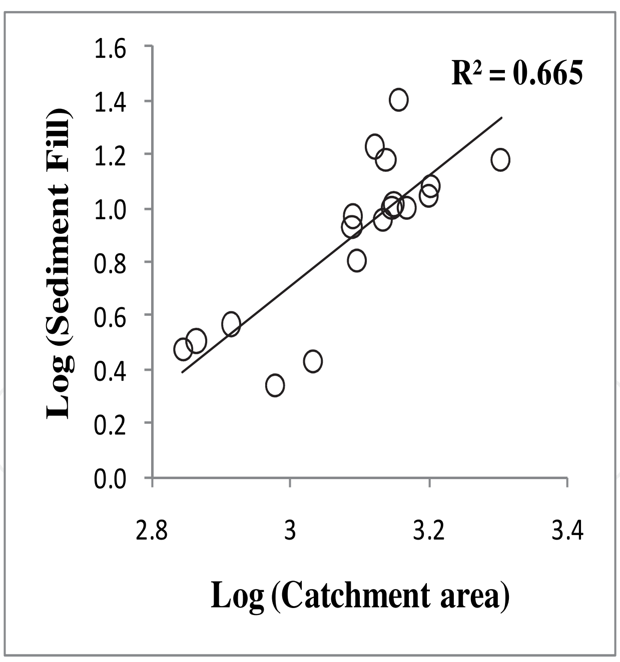

Fig. 3.1. (b) Scatter diagram of log-tranformed values of sediment yield-fill and catchment area for dry climatic zone

3.2 Developed sediment yield prediction equations

Sample regression analysis result for dry climatic zone is presented in Tables 3.2.1 & 3.2.2 below:

Regression Statistics	
Multiple R	0.8081451
R Square	0.6530985
Adjusted R Square	0.6442036
Standard Error	0.1655968
Observations	41

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.013449766	2.01345	73.423838	1.67761E-10
Residual	39	1.0694693	0.027422		
Total	40	3.082919067			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.7452	0.05577	49.21851	1.01E-36	2.632384636	2.858019
X variable	0.4313	0.04885	8.568771	1.678E-10	0.319783073	0.5174043

Table 3.2.1. Regression statistics in log scale for both dry and moderate zones data points

From Table 3.2.1 results we have, Log α = 2.7452 ± Standard Error, and thus α would range from 439.20 to 632.27. And if you take the average you will get α = 556.16. Also the value of β obtained as β = 0.4313± Standard Error. β would therefore range from 0.3824 to 0.4802 with the average value 0.4313. The resulting equation will look like (Equation 3.2)

$$SF = 556.2\ A^{0.4313} \tag{3.2}$$

Where; SF= Sediment fill (m^3/yr); A = Catchment area (km^2); α = constant; and β = scaling exponent.

The corresponding graph of sediment fill-yield versus catchment area in dry and moderate climatic zone (all regions analysed) is presented in Fig. 3.2.

One would note from Fig. 3.2 below that the developed equations satisfactorily predict the sediment fill in small catchment at 95 % confidence interval. It is worth noting that a few of the observed sediment fill-yield data points, for instance, for a catchment sizes of 2.8 and 16.5 km^2 from Tabora region (Table 2.2.2) plotted outside the prediction range (*i.e.*, outlier). The author is attributing it to uncertainty in field measurements. As reported in literature, all techniques for estimating reservoir volume incorporate errors (Morris and Fan, 1998). An estimated error of about ±30% in determining reservoir capacity volumes have been reported in Morris and Fan (1998) by various workers. These discussions may suggest that the error observed above could be explained by uncertainty in determining actual sediment fill (reservoir sedimentation rate), (Ndomba, 2007). Such errors are also acknowledged by Mulengera (2008). A set of sediment fill-yield prediction equations for various climatic zones

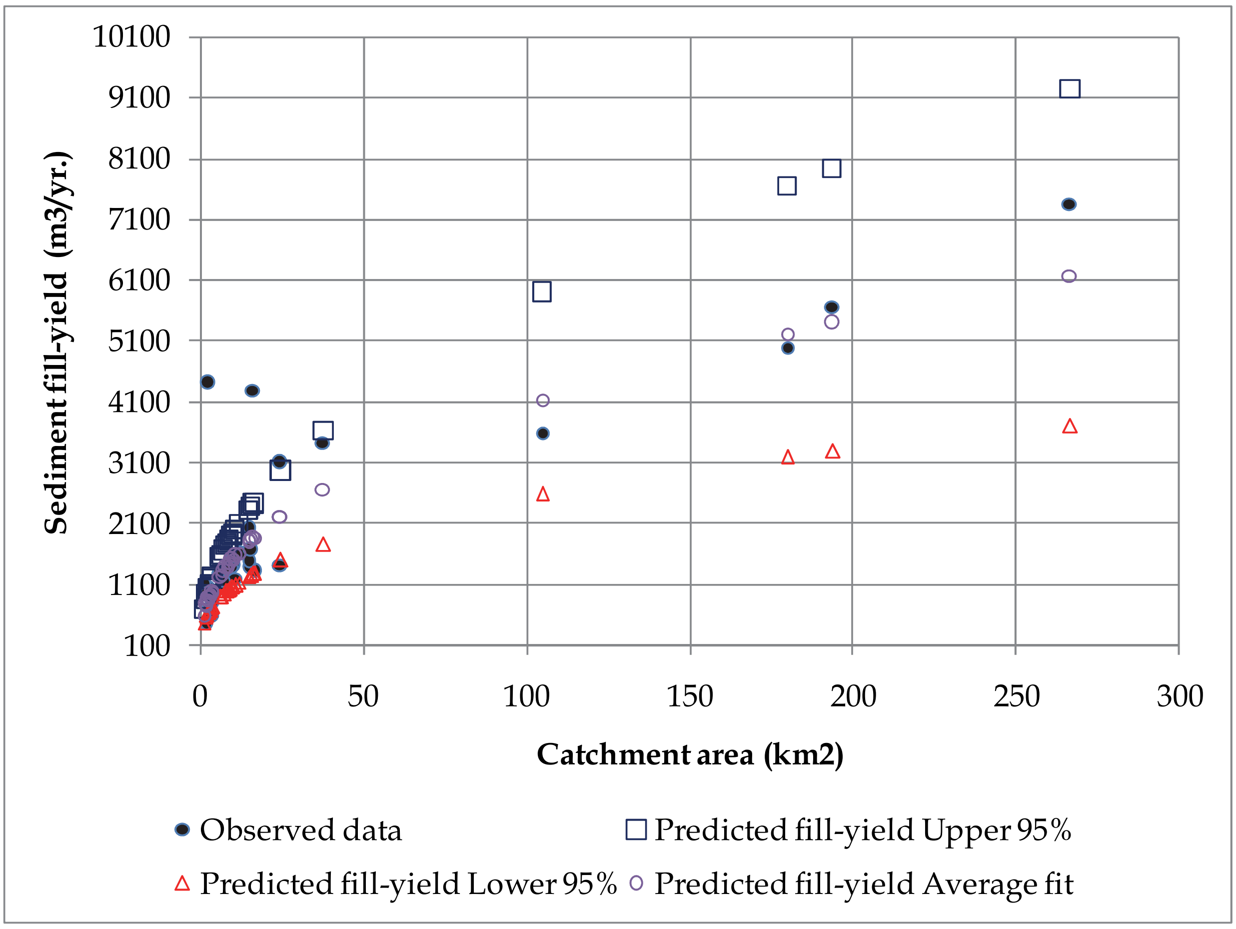

Fig. 3.2. Relationship between sediment fill-yield and catchment area for both dry and moderate climatic zones of Tanzania

were developed in the form of a power function as proposed in section 3.1 above (Table 3.2.2) and as illustrated in Equation 3.2. Besides, the estimated parameter uncertainty bounds are presented in the table. Specific equations for administrative regions are also included.

One would note from Table 3.2.2 below that the performances, as measured by coefficient of determination, R^2, of the developed prediction equations are higher in moderate climate zone than in dry climatic zones. The strength of correlations between sediment yields and catchment area sizes could be categorized as high, moderate and low for Arusha and Tabora, Dodoma, and Dodoma and Shinyanga and Singida regions, respectively. These results suggest that large variance in sediment yields remains unexplained by the developed regressions in dry climatic zone. This may be attributed to high uncertainty in representations of long term sediment yields in catchment with high temporal variability of rainfall intensity, runoff and sediment (Mulengera, 2008). However, independent analysis indicates that sediment fill-yield data used for the dry climatic zones are good in space representation with coefficient of variation, CV, between 23 and 26 in percent. The corresponding values for the moderate and all climatic zones (*i.e.*, dry and moderate) range from 64 to 128 in percent. The high sediment yields for Arusha region were expected as the soils in the region are mostly recent volcanic ash and/or highly erodible. The overall

Climatic zone	Region (s)	No. of data points, n	Range of α=Coefficient ± Standard Error	Average values of α	Range of β =Coefficient ± Standard Error	Average values of β	Sediment Fill/Yield prediction Equation (SF or SY=αA^{β})	R^2
Dry climatic zones	Dodoma, Shinyanga, & Singida	18	508.42 – 663.8	580	0.3712 – 0.4914	0.4313	SF = 580A$^{0.4313}$	0.4586
	Dodoma	13	471 - 815	619.6	0.0636 – 0.3288	0.1962	SF = 619.6A$^{0.1962}$	0.5708
Moderate climatic zone	Tabora	17*	505 - 802.8	637.2	0.2989- 0.4745	0.3867	SF = 637.2A$^{0.3867}$	0.7591
	Arusha	11	333.43 – 31974.22	3264.37	0.4609 – 0.5613	0.511	SF = 3264.4A$^{0.511}$	0.7689
Dry and Moderate zone	All regions analyzed**	41	439.2 – 632.27	556.16	0.3824 – 0.4802	0.4313	SF = 556.2A$^{0.4313}$	0.7318

Note:
* Only 70% of data points for Tabora region were used to fit the regression relationship. Thirty percent (30%), i.e. 7 data points were used for validation purposes.

** The data for Arusha region was not included in fitting the regression for all regions (i.e. dry and moderate climatic zone) as it presents itself with unique soil/erodibility characteristics as discussed under section 2.1 of this chapter..

Table 3.2.2. A summary of developed sediment fill-yield prediction equations for small catchments in Tanzania

relationship developed from data collected from both dry and moderate climatic regions combined has an improved performance according to R^2 of 0.732 as compared to 0.451 for dry climatic zone alone. This could be partly due the fact that the number of data points used to fit the regression is adequate for robust relationship as recommended by Statsoft (2011). However, the author would like to recommend the use of a specific equation for particular purpose/climate, especially Arusha region, as they have been developed. Validation result for the developed prediction equation was much better than during model training phase with R^2 of 0.873. This was attempted only to regions/climatic zone/region where splitting of data into 70% and 30% for calibration and validation was possible, that is Tabora. The number of observations used for this purpose was 7 (serial numbers 18 through 24 in Table 2.2.2).

Although the performances of the developed Regional Regression Relationships are satisfactory, the author caution the reader, as supported by Morris and Fan (1998) that these equations express only the general relationships between independent variables and the sediment yield-fill and should therefore be used only for preliminary planning purposes or as a rough check. Because these equations reflect regional average conditions, the actual yields will tend to be higher (or much higher) than predicted in erosive areas and lower than predicted in areas of undisturbed catchments. Local site-specific conditions can influence sediment yield much more than drainage area or runoff, for instance.

4. Conclusions and recommendations

4.1 Conclusions

This study uses readily available data on catchment area and reservoir sediment fill and/or sediment yield to calibrate the prediction equations' parameters by regression analysis approach. The influence of rainfall and/or runoff as important input variables were indirectly captured by developing and grouping the equations with respect to their climatic zones. The equations were validated and parameter uncertainty bounds estimated. The data set was split into 70% and 30% proportions for calibration and validation purpose, respectively. The measured and predicted reservoir sediment fill-yield rates have satisfactory to good correlations with Coefficient of determination , R^2, between 0.46 and 0.77 with a degree of freedom of, n, 11 to 41 at probability level of significance, p, of 5%. R^2 of 0.87 at n equals 7 was achieved in one of the validation experiments in moderate climatic zone. Although the performances of the developed Regional Regression Relationship are satisfactory, the author would like to caution the reader that these equations express only the general relationships between independent variables and the sediment yield-fill and should therefore be used only for preliminary planning purposes or as a rough check.

4.2 Recommendations

It should be noted that in this work the study area was ill-defined as the wet climatic zone of Tanzania was not adequately represented. Notwithstanding a satisfactory performance achieved, this chapter recommends both extending the data set to cover the wetter regions and incorporating other parameters affecting sediment yield for processes studies and better prediction in the follow up research. This can be achieved if more data such as sediment Particle Size Distribution (PSD), bulky density, dam trap efficiency, catchment environmental variables (*i.e.*, land cover/use, slope, slope length, runoff, rainfall, etc), and operational data and geographic locations of the small dams could be supplemented.

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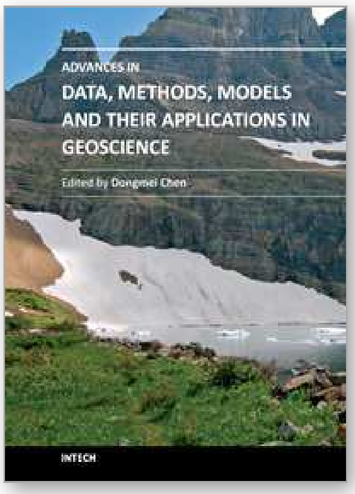

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With growing attention on global environmental and climate change, geoscience has experienced rapid change and development in the last three decades. Many new data, methods and modeling techniques have been developed and applied in various aspects of geoscience. The chapters collected in this book present an excellent profile of the current state of various data, analysis methods and modeling techniques, and demonstrate their applications from hydrology, geology and paleogeomorphology, to geophysics, environmental and climate change. The wide range methods and techniques covered in the book include information systems and technology, global position system (GPS), digital sediment core image analysis, fuzzy set theory for hydrology, spatial interpolation, spectral analysis of geophysical data, GIS-based hydrological models, high resolution geological models, 3D sedimentology, change detection from remote sensing, etc. Besides two comprehensive review articles, most chapters focus on in-depth studies of a particular method or technique.