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DEVELOPING AN EXCELLENT SEDIMENT RATING CURVE FROM ONE HYDROLOGICAL YEAR SAMPLING PROGRAMME DATA: APPROACH

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Abstract: This paper presents preliminary findings on the adequacy of one hydrological year sampling programme data in developing an excellent sediment rating curve. The study case is a 1DD1 subcatchment in the upstream of Pangani River Basin (PRB), located in the North Eastern part of Tanzania. 1DD1 is the major runoff-sediment contributing tributary to the downstream hydropower reservoir, the Nyumba Ya Mungu (NYM). In literature sediment rating curve method is known to underestimate the actual sediment load. In the case of developing countries long-term sediment sampling monitoring or conservation campaigns have been reported as unworkable options. Besides, to the best knowledge of the authors, to date there is no consensus on how to develop an excellent rating curve. Daily-midway and intermittent-cross section sediment samples from Depth Integrating sampler (D-74) were used to calibrate the subdaily automatic sediment pumping sampler (ISCO 6712) near bank point samples for developing the rating curve. Sediment load correction factors were derived from both statistical bias estimators and actual sediment load approaches. It should be noted that the ongoing study is guided by findings of other studies in the same catchment. For instance, long term sediment yield rate estimated based on reservoir survey validated the performance of the developed rating curve. The result suggests that excellent rating curve could be developed from one hydrological year sediment sampling programme data. This study has also found that uncorrected rating curve underestimates sediment load. The degree of underestimation depends on the type of rating curve developed and data used.

Keywords: Actual sediment load; sediment rating curve; sediment sampling programme; statistical bias estimator; sediment load correction factor

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INTRODUCTION

At least for large rivers, sediment-rating curves could be used to generate reasonably accurate (≤15–20%) suspended sediment flux estimates for quarterly timeframes or greater (Horowitz, 2004). However, attempts to use a sediment flow data collected from many years by other researchers have not been possible because of a wide range of reasons. For instance, Syvitski *et al.* (2000) have reported that of the rivers that have been gauged worldwide, very few are presently being monitored for sediment load. Summer *et al.* (1992) have shown that long term monitoring does not necessarily mean better results. Rating curve methods have also been reported to underestimate the actual loads (Ferguson, 1986; Walling, 1977; Walling & Webb, 1981; Thodsen *et al.*, 2004). In cases of developing countries such as Tanzania, long term monitoring or conservation campaigns have been reported as unworkable options (Ndomba, 2007). Besides, other workers have shown that the use of different field sampling procedures might result into un-similar results (Yuzyk *et al.*, 1992; Thomas, 1985).

The most common way of combining intermittent concentration data with continuous discharge data uses a rating curve to predict unmeasured concentrations from the discharge at the time (Ferguson, 1986; Walling, 1977). A suspended sediment rating curve or transport curve is usually presented in one of two basic forms, either as a suspended sediment concentration/streamflow or as a suspended sediment discharge/streamflow relationship (Walling, 1977). In both cases a logarithmic plot is commonly used, with Ordinary Least Squares (OLS) regression employed to fit a straight line through the scatter of points (Walling, 1977). In most cases, rating curves are constructed from instantaneous observations of discharge and either sediment concentration or load, but several specific variants have been proposed (Walling, 1977). Colby (1956) has classified rating relationships, according to temporal resolution of the data, into instantaneous, daily, monthly, annual and flood period curves and, according to particle size criteria, into clay-silt ratings and sand-sized ratings. Other researchers have subdivided instantaneous data according to stage and season, constructing separate rating relationships for rising and falling stages (Loughran, 1976) and for various times of the year (Hall, 1967; Miller, 1951) as reported in Walling (1977). The procedure used to combine the rating relationship and the associated streamflow data could give rise to underestimation of loads by as much as 50 percent and the inherent inaccuracy of using a rating curve to predict sediment concentration or loads could give rise to errors of as much as +50 percent (Walling, 1977). As Ferguson (1986) suggests that most estimates of river load by rating curve method will have been too low.

Other scientists have proposed a statistical bias-correction factor to remove the degree of underestimation by rating curve method (Duan, 1983; Ferguson, 1986). The latter method is meant to correct actual loads, which are underestimated, because the proposed correction factor is always greater than unit (Ndomba, 2007). Walling (1977) has reported cases where sediment loads are overestimated by the rating curve method. Also, Walling & Webb (1988) research findings have indicated that statistical bias-correction procedures do not provide accurate estimates in their study rivers. That is other sources of error associated with rating curves are more important in producing inaccurate estimates. Thus a general method is still needed where overestimation could be corrected as well.

Based on the discussions above, one would note that there is no consensus on how to develop an excellent sediment rating curve. With particular example underestimation of sediment load by the rating curve is still a deadlock. To date, little has been done by others to examine the adequacy of a short-term sampling programme data on developing rating curve. This paper therefore discusses on how the excellent rating curve was developed and validated for 1DD1 subcatchment of PRB in Tanzania.

MATERIAL AND METHODS

Description of the Study Area

The 7280 km^2 1DD1 subcatchment is located in the upstream of Pangani River Basin (PRB) (**Fig. 1**). The main outlet of the catchment is situated at 1DD1 flow gauging station. The catchment covers mainly Hai, Arumeru, small portion of Monduli and Simanjiro districts in Arusha region and the district of Moshi in Kilimanjaro region. Population densities of more than 600 persons/km^2 are found on the slopes of Mt. Kilimanjaro. More than 50% of the basin, mainly the lowland plains are arid or semi-arid with an annual precipitation of 500–600 mm/year. High levels precipitation can be found in the southern slopes of the mountain areas with an annual precipitation of between 1000 – 2000 mm/year. The rainfall pattern is bimodal with two distinct rainy seasons, long rains from March to June and Short rains from November to December. Rivers and streams draining the 1DD1 run generally in the North-South and South East directions. This includes the flow from Mt. Kilimanjaro, West of Moshi, flows from the Kikuletwa, Kware Springs and streams from the Southern slopes of Mount Meru.

1DD1 subcatchment contains spring discharges, which include Chemka spring having a yield of 10 m^3/s located 10 km East of Kilimanjaro International Airport (KIA) and is part of Rundugai springs, Shiri spring (0.2 m^3/s) and Nsere (0.16 m^3/s). The study area forms a headwater of the main PRB. The mountain slopes of Mt. Kilimanjaro can be divided into five ecological zones,

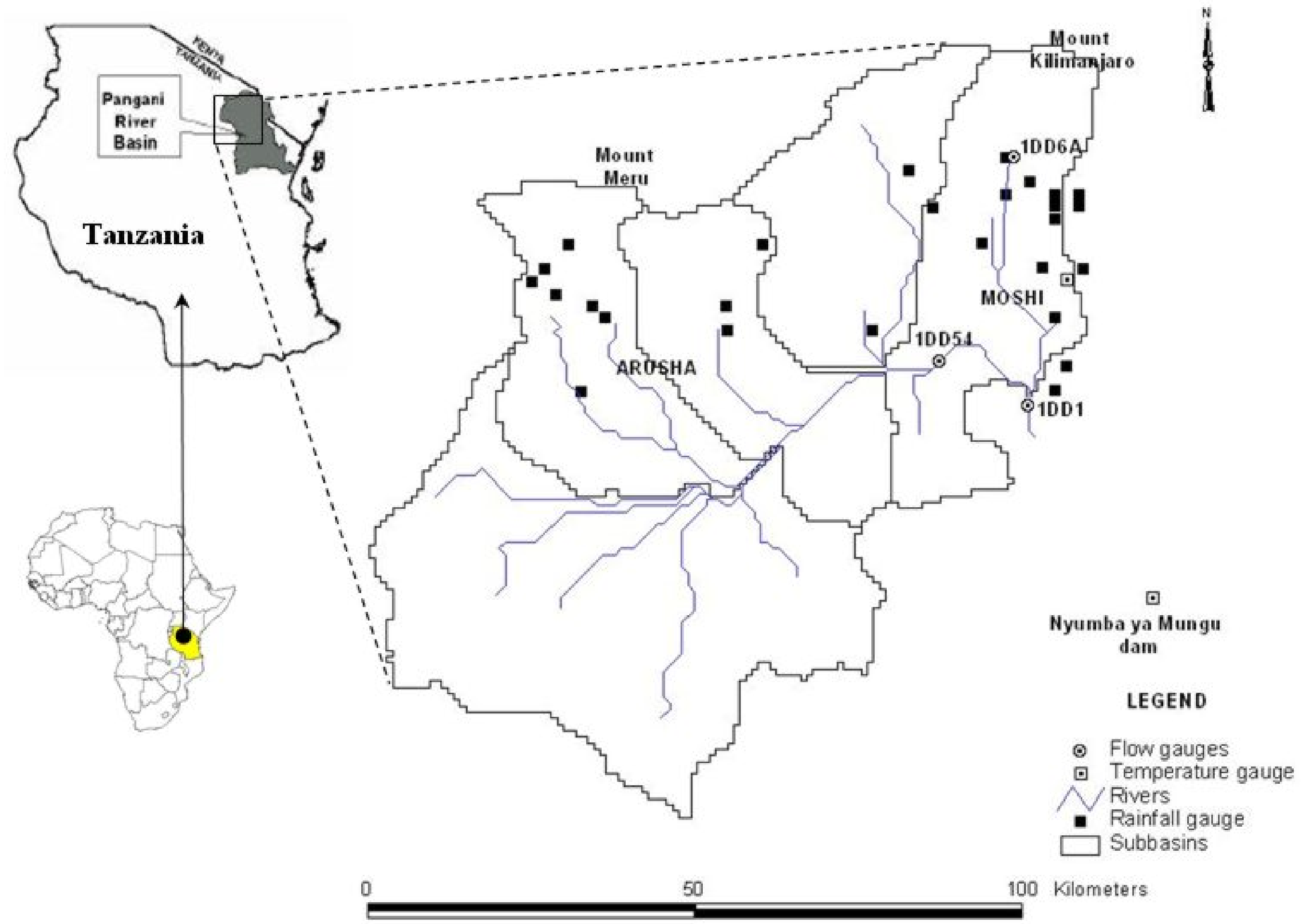

Fig. 1 Location map of the 1DD1 subcatchment in the upstream of Pangani River Basin.

the lower slopes (900–1800 masl), the forest (1800–2800 masl), the heath and moorland, the highland desert (4000–5000 masl) and the summit (above 5000 masl). The surrounding area on the plains below can be classified as tropical savannah. The human settlements and agricultural activities are located on the plains and on the lower slopes between 900 and 1800 masl.

The area above this level forms the Forest Reserve and the Kilimanjaro National Park. In this area, there are, in principle, no settlement, or human activities related to agriculture and land use. Fires, illegal timber collecting, land pressure and over usage of natural resources are among Mt. Kilimanjaro's biggest problems.

Based on the Soil Atlas of Tanzania (Hathout, 1983) and analysis by Ndomba (2007) the main soil type in the upper PRB is clay with good drainage. Sampling Design and Data Analysis

Sediment flow data for rating curve development was collected from 1DD1 flow gauging station (**Fig. 1**). The sampling program runs all year-round. Generally, the selected site is ideal based on the fact that the hydrological information can be obtained or extracted from the neighbouring gauging stations, as pre-requisite information in sediment sampling program planning (Ndomba, 2007). An Automatic sediment-pumping sampler (ISCO 6712) with a spare battery collects sub-daily suspended sediment samples at 1DD1 station (**Fig. 2**). A daily observer's sample is also collected using a Depth integrating sampler (D-74) at midway of sampling cross section, location number 5 in **Fig. 2**.

The equipments used in this study are known to sample sediment concentrations iso-kinetically (Bogen, 2004; Gurnel *et al*., 1992; and Yuzyk *et al*., 1992). The ISCO sampling tube head is installed in a turbulent river as recommended by Bogen (1992). The gauge height at zero flow and historical lowest water gauge height are 0.51 m and 0.88 m, respectively. Therefore, the sampling tube head is located 0.08 m below the lowest observed water stage and 0.29 m above the riverbed. Intermittent cross section samples, for determination of cross section coefficient and Particle Size Distribution (PSD), are taken along the channel width using Depth Integrating sampler (D-74) trailed over cableway suspension facilities (**Fig. 2**).

The site is about 25 m long and with an average water surface top width of 18 m. The water samples were filtered through Whatman GF/C glass fibre filters with a nominal retention diameter of particles of 0.65μm.The composite sample from Equal-Transit Rate (ETR) procedure was used to determine the correct mean sediment concentration. The cross section coefficient is equal to the ratio of the average

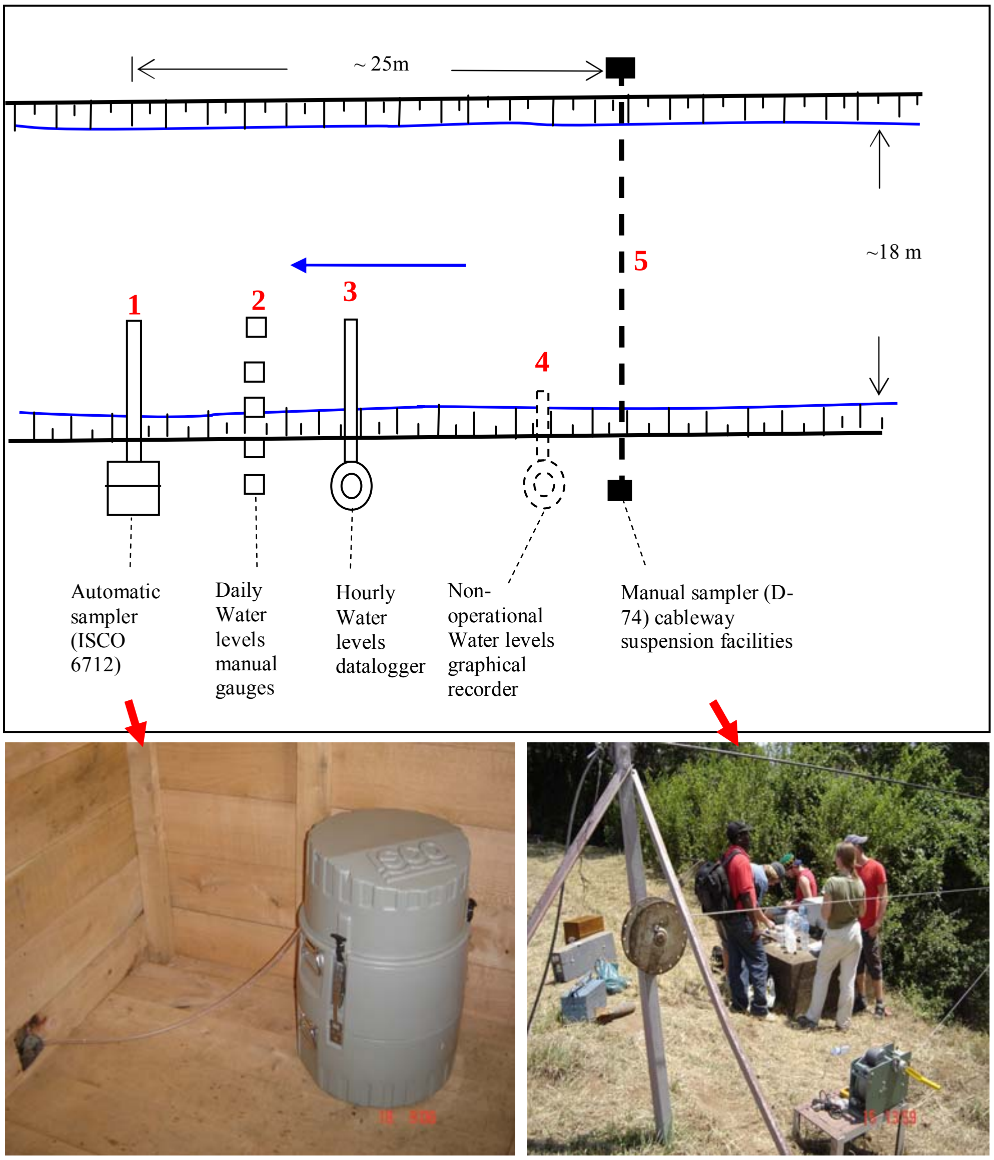

Fig. 2 1DD1 flow gauging station layout design and suspended sediment sampling equipment.

concentration from the composite sample to the concentration of the single-vertical samples (Guy & Norman, 1970; MoW, 1979). Since, correction coefficient may not be the same for low discharges as for the high discharges, thus why in this study wet and dry seasons coefficients are derived and analyzed. As a rule, coefficients within five percent of unit are not applied unless they are consistently high or low for long periods of time (Guy & Norman, 1970; MoW, 1979).

This study assumes that sediment flow data from automatic sampler could give estimates of actual sediment load. A bias correction factor is derived as the ratio between actual load and sediment load by the Rating curve. Besides, a statistical bias correction as recommended by Ferguson (1986) was also determined and used. This study uses instantaneous sub daily sediment samples from ISCO sampler to derive a rating curve (**Table 1**).

In this study, different procedures of constructing rating curves have been tested. Some of these are: use of all data points, season, stage and stage and season. The rating relationships have been determined using linear least-square regression of the logarithmic transformed data.

Table 1. A summary of sediment flow data as sampled by ISCO 6712 sampler at 1DD1 site (i.e. 291 data points)

Statistic	**Sampling period**	**Suspended sediment concentration [mg/l]**	**Gauge Height [m]**	**Streamflow discharge [m^3/s]**
Maximum	March 18 - November 10, 2005	9110.0	4.442	256.533
Minimum		16.0	0.890	12.192
Mean		282.5	1.323	34.794
Standard Deviation, STD		801.7	0.485	30.018
Coefficient of Variation, Cv (%)		283.8	36.693	86.271
Standard Error of the Mean, EM		47.0	0.028	1.760

This follows the approach adopted by many previous workers and can be justified on statistical grounds in terms of data normality, linearity of the relationship and considerations of homoscedasticity (Walling, 1977). The performances of these relationships were tested against Coefficient of Determination (r^2) and Standard Error of Estimate (STEXY).

The results from short-term sampling programme were compared to reservoir survey information. The analysis did not apply the sediment delivery factor since the approach involves numerous problems and there is a need for a more refined approach (Ndomba, 2007).

RESULTS AND DISCUSSIONS

Developed rating relationship/curves

The best three rating curves and their regression coefficients are presented in **Table 2** below. One would note from **Table 2** that generally stage rise/fall rating curves performs better both in r^2 and STEYX. However, the difference in STEYX indices between seasonal and rise/fall is not significant. The analysis of the single hydrological events suggests that the hysteresis is common with counter clockwise loop dominating (Ndomba *et al.*, 2007; Ndomba, 2007) Therefore, stage rise/fall rating is appropriate. It should be noted that correction factors for ISCO load and Ferguson (1986) methods have been derived from hourly sediment flow data and instantaneous sediment/flow discharge data, respectively.

A bias correction factor is applied in the respective rating curve equations as a coefficient (**Eq. 1**):

$$Q_s = aQ_i^b \eta_i \qquad (1)$$

where, η_i is a load bias correction factor; a, *b* are the normal regression coefficients of rating curve; Q_i is streamflow (m^3/s) and Q_s is sediment load (t/day). Ferguson (1986) method computes a statistical bias estimator based on instantaneous sediment concentration or discharges data used to develop the rating. An alternative method and used by many others is that of using actual sediment load from turbidity meter and ISCO sampler measurements to correct the load estimated by rating curves (Walling & Webb, 1988).

Typical bias correction factors for this study using both methods are presented in **Table 2** above. It can be learned that a range of values of correction factors can be derived using the same data set. That might be a reason why other workers have shaded doubt on some bias correction factor methods. For instance, Walling & Webb (1988) noted that statistical bias-correction factors did not remove the degree of underestimation for three rivers in Devon, UK.

Besides, other workers have concluded that site-specific relationships are required and that no universal correction is applicable (Yuzyk, *et al.*, 1992).

It should be noted that the ongoing study intends to estimate a long term sediment yield using readily available historical daily mean streamflow. Thus all relationships in **Table 2** were applied for the period of intensive sampling using the latter temporal resolution and compared to actual load. Because, some workers still doubt the applicability of Ferguson (1986) statistical bias correction factor method, a set of these results using hourly streamflow data for the same period is also included (**Table 3**).

The result in **Table 3** below suggests that “All points” rating corrected by ISCO load is the best over the rest in estimating actual load using mean daily stream flow. Ferguson (1986) method correction factor can estimate the actual load within –5% and +16% to the actual load using seasonal or stage based ratings based on mean daily flow discharges. However, actual load can best be estimated from hourly streamflow data using stage and season based ratings within –9% and +18% error, respectively. This suggests that Ferguson (1986) correction method is reliable and cheap method of correction when both appropriate rating relationships are used and hourly streamflow data is available. The caution should however be taken that the method is not suitable when applied to *all points* rating curve.

Probably, one would learn that the performance of the Ferguson (1986) method depends on the type of data used to derive the correction factor.

One will note from **Fig. 3** below that the rating curve corrected by ISCO load is higher than Ferguson (1986) and Ordinary Least Square (OLS) based curves. The OLS based rating is always plotted under the corrected curves. Others have reported the same observation and it may be used as a direct indication that the uncorrected

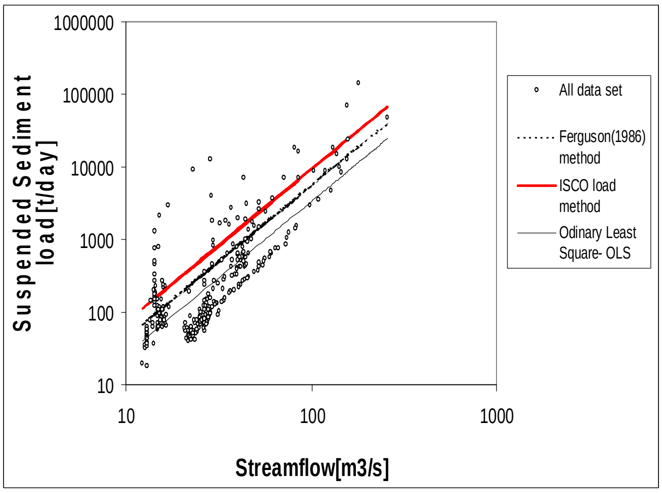

Fig. 3 “All points” sediment rating curve at 1DD1 gauging station.

Table 2. A list of developed rating curves and their performance and correction factors for 1DD1 flow gauging station

SN	Rating type	Flow condition	Regression coefficients		Performance indicators		Load correction factors (η_i) methods	
			a	*b*	r^2	STEYX	ISCO load	Ferguson (1986)
1.	All points	All	0.2055	2.1066	0.61	8774	2.78	1.66
2.	Season (Q classes)	$Q < 20$ m^3/s	0.0003	4.7198	0.17	7631	1.23	1.45
		$Q > 20$ m^3/s	0.0072	2.9711	0.74			1.46
3.	Stage Rise/fall	Rising	0.2286	2.2271	0.63	7696	1.58	1.80
		Falling	0.0077	2.9148	0.81			1.22

curves would definitely underestimate the actual load. Despite the excellent performance of stage and season based relationships on hourly streamflow data, this study however, uses *all points* rating (**Fig. 3**) to predict long term sediment yield. This is due to the fact that the available flow data in longer term perspectives is daily mean discharges. The estimated sediment transported load for year 2005 using the "all points" rating curve is 266 611 tonnes and long term (i.e. 37 years) sediment yield at 1DD1 is 12.1Million tones (Ndomba, 2007).

It should be noted that Regression parameters and respective correction factors are presented in Table 1 above. You will note in **Fig. 3** that there is significant scatter during medium and the low flows but with satisfactory defined relation between sediment load and discharge during the higher streamflows. This river is a perennial stream, in which flow is sustained throughout the year by springs at an average of 10 m³/s. It has been assumed that the data set available for rating curve construction represents a near-optimum data collection scheme and that estimates of the errors involved in calculating sediment loads will be minimum estimates. Other workers such as Walling (1977) have done little as well, in quantifying errors due to varying number of data points.

The computed long-term sediment yields based on rating curve and reservoir survey are comparable within a relative error of about 20% (**Table 4**). It should also be noted that this analysis does not include bed load correction concept.

According to Maddock's classification to determine unmeasured load as presented in Garde & Ranga Raju (2000), for fine grained transported sediments (Ndomba *et al.*, 2007) as the case for this study the unmeasured load would range between 2 to 8% of measured. Therefore, authors are convinced that for most practical engineering problems the results from **Table 4** are sound. Because, the corrected rating curve have been applied to a larger catchment with 97.5% contribution of sediment load into the reservoir (Ndomba, 2007). The result also suggests that the corrected rating curve could also be used to predict the seasonal and inter-annual sediment yield rates (Ndomba, 2007). However, year-to-year changes in exponent of the sediment rating regression lines curve have been reported by many others (Syvitski *et al.*, 2000; Bogen, 2004). For instances, the interannual variability in the sediment rating parameters have been attributed to changes in sediment availability in the catchment by Bogen & BØnsnes (2003). Therefore, the application of the proposed approach would be limited to catchments where no adverse changes in landuse/landcover or landscape modification have taken place.

Table 3. Percent of estimated load to actual load at 1DD1 gauging station

SN	Rating type	ISCO load corrected rating	Ferguson (1986) method corrected rating	
		Mean daily stream flow	Hourly stream flow	Mean daily stream flow
1.	All points	99	60	59
2.	Season (*Q* classes)	98	118	116
3.	Stage Rise/fall	89	91	95

Conclusions and Recommendations

This study has shown that rating curve based on Ordinary Least Squares (OLS) method underestimates sediment load**.** The degree of underestimation depends on the type of rating curve developed and data used. Long term estimates of sediment yield rates based on corrected rating curve and reservoir survey and sampling are comparable within a relative error of 20%. The long-term predicted sediment yield rate for 1DD1 catchment is therefore equal to 327 000 t/year (or 287 000 m³/year).

The result suggests that excellent rating curve could be developed from one hydrological year sediment sampling programme data.

The analysis does not apply bed load correction factor and sediment delivery ratio. It is believed that the quality of this result is attributed to sound design of the sampling programme. Besides, this study was well

Table 4. Comparison between rating curve and reservoir survey based long term sediment yield rate estimates for 1DD1 subcatchment

Method	Sediment yield rate (t/year)	Relative Error (%)
Rating curve	327 000	20
Reservoir survey plus sampling programme*	408 500	

*Ndomba (2007)

guided by other studies in the same basin. As the sediment transport in the basin is characterised by high temporal variability, accordingly, more follow-up researches in this direction are required. For instance, in order to capture high variability of sediment delivery the use of a photoelectric turbidity meter coupled with automatic sediment pumping sampler, ISCO machine, in Pangani river system is proposed to refine the result of this study. The authors would like to note that the issues and approaches discussed in this paper might be transferable.

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