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Generation of a Suspended Sediment Rating Curve of a Himalayan River based on a Long-term Data: A case study of Kabeli River

Sanyam Ghimire [a], Umesh Singh [b], Pawan Kumar Bhattarai [a]

[a] *Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[b] *Hydro Lab Pvt. Ltd., Lalitpur, Nepal*
Corresponding Email: [b] ush@hydrolab.org

Abstract

Suspended Sediment Rating Curve (SSRC) is one of the most cost effective method for monitoring and predicting suspended sediment concentration for water resource project development. This method allows estimating the sediment inflow based on the river discharge - which is relatively easier to monitor. SSRC for most of the projects in Nepal are derived based on the Ordinary Least Square (OLS) method using trend line fit function of MS-Excel, because of its simplicity. The performance of OLS method for Himalayan River has, however, not yet been evaluated because of the lack of availability of the long-term suspended sediment data. This paper investigates different methods for generating the SSRC of a Himalayan River, namely OLS method, bias correction method and optimization method. Kabeli River, a tributary of Tamor River originating from the Himalayan region, was selected as a case study because of the availability of daily suspended sediment concentration and flow data recorded for 8 years. SSRC for Kabeli River constructed by OLS method underestimate long-term sediment load by 54%. The bias correction method significantly improved SSRC but overestimated the sediment load by about 8%. The optimization method provided the closest values to the observed suspended sediment load and thus deemed as the best method of generating the SSRC for the Himalayan Rivers. Analysis of the sediment rating suggests that delivery of sediment is always in supply limitation from the catchment.

Keywords

Sediment Load, Suspended Sediment Rating Curve, Bias Correction, Optimization Method

1. Introduction

The knowledge of sediment load in the river are crucial for development of water resources infrastructures. Analysis of available sediment data is important for proper design and functionality of those infrastructures.

Sediment load is divided into two categories viz. bed load and wash load. The sediments which moves with the river bed are bed load whereas the sediment in suspension are suspended load.

The availability of long term data of Suspended Sediment Load (SSL) worldwide and particularly in case of Nepal are scarce. The main reason for this is that SSL measurement requires skilled human resources, consumes more time and is costlier than discharge monitoring - which can be readily measured by observing the gauge height and correlating with the stage-discharge relation. Sediment sampling is also difficult due to site accessibility issues. Similarly, bed loads are comparatively difficult to measure than suspended load [1]. So, the most general way of linking the intermittent sediment concentration data with continuous streamflow data commonly uses a rating curve to estimate unmeasured concentration from the streamflow [2]. In absence of any other hydraulic or hydrologic parameter, river discharge is best suited and a better proxy for estimation of the sediment load/concentration [3].

Sediment Rating Curve (SRC) - a relation between the river discharge and suspended sediment concentration - is derived from the monitored data. The sediment yield is estimated using the stream hydrograph based on the sediment rating [4]. Rating curves are equally important for physical model studies, particularly for river diversion scheme and headworks. However, till date, there is no consent among the technical reports and literature [5, 6, 7] to produce a comprehensive sediment rating curve using the observed data in the Himalayan Rivers. Similarly, SRC is a black box model where the associated parameters have no physical significance [8]. Ordinary Least Square (OLS) approach is the most common method for deriving a suspended sediment rating curve [6, 7, 5]. The method, however adopted in preparing sediment rating curve tend to underestimate the sediment load by about 50% [2, 9]. This bias in estimation can be eliminated by using different bias correction factor [10, 2].

Developing such rating curve is important to know the sediment inflow to the river by using river discharge alone. Sediment rating curves are also used as convenient methods of predicting sediment concentration and loads in reservoir sediment management [4]. The applicability of different methods, however, is not investigated in detail. So, the purpose of this paper is to assess available procedures of constructing the sediment rating curves from long term suspended sediment concentration data reducing the potential magnitude of associated errors.

2. Methodology

2.1 Study Area

Kabeli River Basin is located at the eastern part of Nepal in Province-1. Kabeli River is one of the tributaries of Tamor River- a major tributary of the Sapta Koshi River. The Kabeli Basin is located in between latitudes 27°13’ and 27°32’ N and longitudes 87°43’ and 88°04’ E. The main reason for selecting it as the study area is the availability of relatively long-term field measurement of sediment fluxes and river flow. In addition, the Kabeli River also represents a typical case of a snow-fed river where most of the water resource projects in Nepal have been envisaged. The location map of the study area is shown in Figure 1 and the upstream view of the river is shown in Figure 2. The catchment of Kabeli River has an elevation ranging from 560 to 5487 masl and the area is 862 km^2 at the intake location of Kabeli hydropower where a streamflow and sediment sampling station is set up. The catchment area above the permanent snow line (5000 masl) is only about 1 km^2.

Figure 2: A view of Kabeli River 20 m downstream of sampling location (Year 2020)

Kabeli basin is highly influenced by the monsoon (Jun-Sept) that accounts for around 76% of mean annual rainfall. Higher amount of precipitation is observed in the north-east part of the catchment.

About 56% of the catchment is covered by forest. Similarly, agriculture covers around 20% of the total area. The agricultural activities are located on lower slopes between 560 to 2000 masl. Remaining 24% of the catchment is covered by grassland, shrubland and snow covered area.

Based on the Soil and Terrain Database (SOTER) the main type of the soil is Humic Leptosols and Eutric Cambisols with area coverage of 39% and 38.9% respectively. These soils have moderate infiltration rates and moderate well to well drainage characteristics.

The major geological formation in Kabeli Catchment is Seti Formation, Himal Group and Taplejung Granites [11] comprising minerals like quartz, feldspar, and granite in abundance.

2.2 Data

Streamflow data of the river was recorded by Kabeli Energy Limited from May 15, 2010 to January 14, 2018. Initially a flow rating curve was generated. After that, the river discharge was derived by using the rating equation (Equation 1) and the recorded gauge heights. The stage was recorded twice a day at 8 AM and 5 PM.

$$Q = 3.7(H - 551.3)^{2.78} \tag{1}$$

Where, Q is River Discharge in m^3/s, H is Water surface elevation in masl, The bottom elevation of the gauge is 552.6 masl. Therefore, $H = 552.6 + G$.

A Swedish type hand held sampler was used to abstract suspended sediment samples for

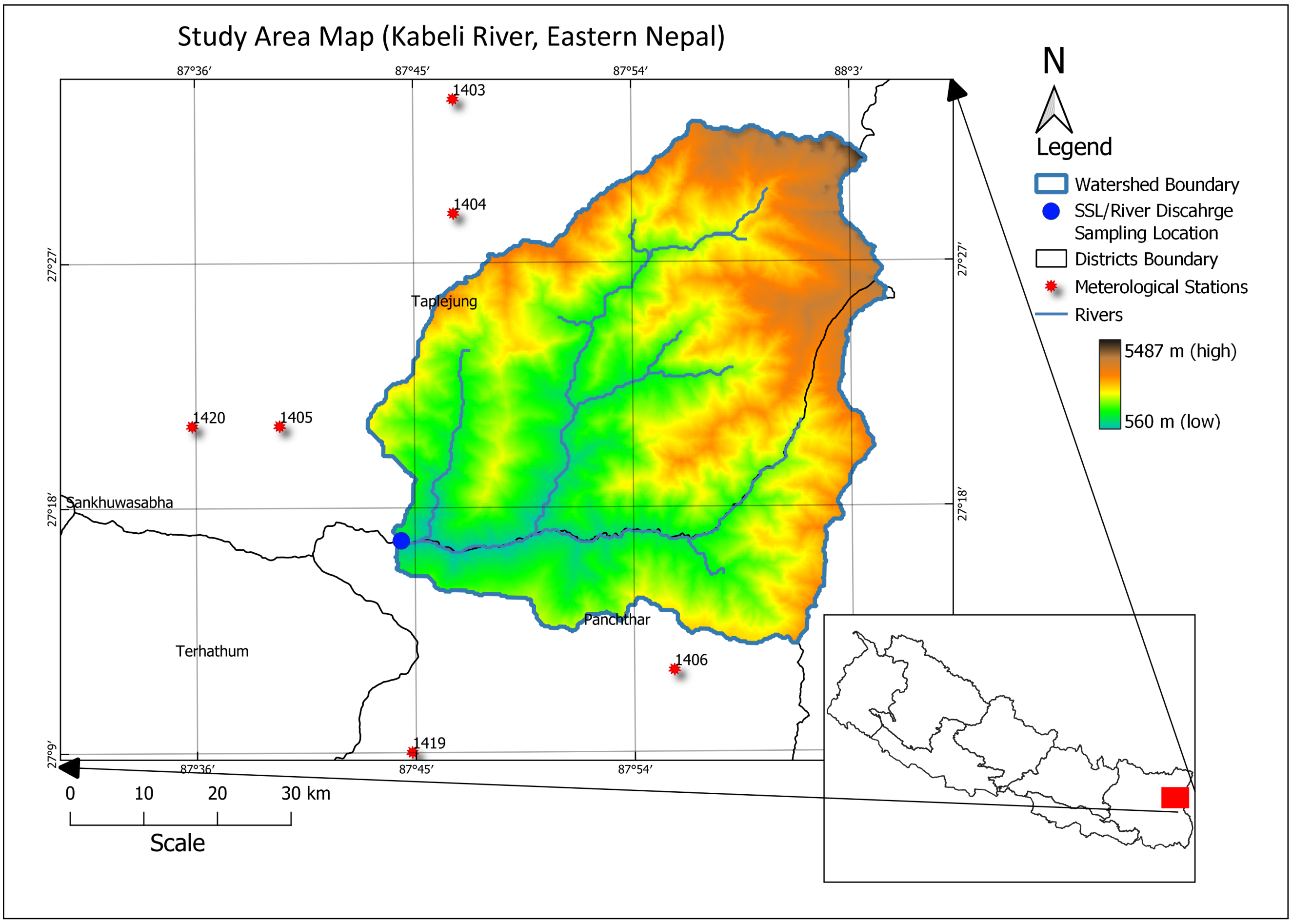

Figure 1: Location Map of Study Area

concentration analysis. The sampler fixed on an extension rod immersed at about 0.5m below the surface of the water in the river was used to abstract the sample in the bottle which was fixed on the sampler. Two regular samples per day were collected at 8 AM and 5 PM from 22 April, 2010 to 4 August, 2018. Altogether, 4572 samples were abstracted during the entire sampling period. Additional samples were also collected during the flood when the water in the river was "dirtier" than normal in between regular sampling period. The sediment concentration was monitored through out the year with some exceptions in year 2012 and 2014. A representative sediment sampling extraction process is shown in Figure 3. In addition to the sampling date, sampling time, water temperature and gauge height were also recorded. The standard filtration method was used to analyze the sediment concentration. Whatman filter paper of 11 micron porosity was used for the filtration analysis [12].

Table 1: A summary of observed suspended sediment concentration and flow data at Kabeli intake site (i.e. 4572 data points)

	SSC (ppm)	Gauge Height (m)	Discharge (m^3/s)
Mean	404.12	0.85	34.75
Standard Deviation	1468.69	0.46	20.75
Minimum	0.00	0.21	11.63
25%	15.00	0.43	16.98
50%	45.00	0.77	27.96
75%	262.00	1.23	48.85
Maximum	46137.0	2.60	162.69

This study is based on the analysis of the available long-term field observation data and sediment yield estimation model. The prime data used in this study i.e. sediment concentration and discharge is collected by Kabeli Energy Ltd. It is believed that the procedure of data sampling adopted by such a renowned institution is in a standard way. It is also assumed that the data is collected, processed and analyzed in a consistent manner. All analysis of sediment concentration are done on raw non-interpolated data. The quality and representativeness of data may vary but is considered representative for the whole water depth and river cross section. A summary of observed sediment and river discharge data is given in Table 1. Likewise, the time series plot of observed discharge and suspended sediment concentration of the entire sampling period is shown in Figure 4.

Figure 3: Suspended sediment sampling process in the field [12]

2.3 Analysis

Sediment rating curves can be used to construct reasonably accurate (up to <15-20%) suspended sediment concentration estimates for one fourth of the timeframes or even greater, which is true for large rivers [13] as cited in [14]. In most of the studies, sediment-discharge relations (rating curve) are usually defined as a power function [15, 16, 17].

$$SSC = aQ^b \tag{2}$$

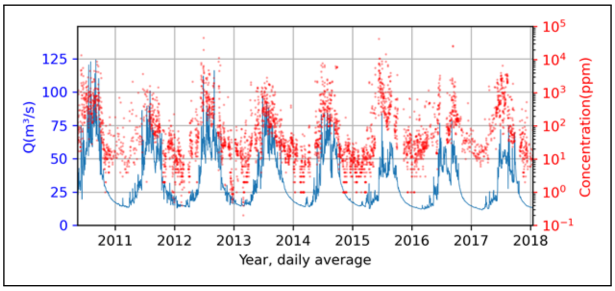

Figure 4: 8 years (2010-2018) temporal variability of discharge and sediment concentration. Daily river discharge hydrograph (blue) and suspended sediment concentration (red with scatter plot). Axis representing sediment concentration in logarathmic scale.

Where, SSC is suspended sediment concentration (ppm), Q is water discharge (m^3/s), a and b are the site specific parametric values. Here the coefficient and exponent, a and b respectively, have no physical meanings. However, some literatures have physical interpretation on them. As cited in [8, 18], the coefficient a is related to the susceptibility of erosion whereas b factor is related to erosion and transport capacity of rainfall and river flow [19].

Sediment Load is calculated using

$$SSL_{1-2} = \left[Q_1 \times C_1 \times \frac{t_2 - t_1}{2} + Q_2 \times C_2 \times \frac{t_2 - t_1}{2} \right] \frac{60 \times 60}{10^6} \tag{3}$$

Where, SSL_{1-2} is Suspended sediment load between two consecutive measurements (tons), Q_1 and Q_2 are River discharge at time t_1 and t_2 respectively (m^3/s), t_1 and t_2 are time of two consecutive measurements (hrs.). Daily Sediment Load is obtained using:

$$SL = 0.0864 \times Q \times SSC \tag{4}$$

It is generally assumed that the process of sediment transport (erosion and deposition) in catchment has been the same over the time of observations and will continue to be the same in future. However, this supposition is not always true in case of sediment transport and the necessary assumptions of stationarity may sometimes need to be investigated [9]. Therefore, some of the qualitative methods are used to screen out the poor-quality input data to prevent faulty output from the analysis.

In this regard, stationary analysis is done to screen out the clustered data that do not represent the general trend of sediment concentration. If the data for some year is clustered in one part or in any other peculiar region of the plot, it is not regarded in sediment concentration analysis. Referring to Figure 5, the red scatters shows the suspended sediment concentration and respective discharge of specified year and blue clusters show the same for rest of the years. It is to be noted that the sediment sampling program did not continue throughout all seasons over the years. Here, it can be observed that the dispersion of data is satisfactorily uniform over the observational years. So data from all years are taken into consideration for sediment concentration analysis.

Serialized correction is also applied if there are different sediment concentration for same magnitude of discharge in a single day which would otherwise over-represent the data for the very day when more concentrations are sampled. Similarly, tendency to have relatively more data in recent times is generic. Consequently, these numerous newer samples gets over-weighed. So, these temporally clustered data points were removed by visual inspection of the sediment concentration time series.

2.4 Sediment Rating

In this study, different methods of constructing sediment rating curve are applied. It is a customary practice of using Ordinary Least Square (OLS) for any equation to obtain the required variable. The main problem of aforementioned power equation (Equation 2) used in rating analysis is that it introduces a statistical bias which underestimates the load by a considerable amount (more than 50% when full time-series of data is available) [20, 2, 21, 9]. So, different correction methods available in the literatures can be used to improve the accuracy of estimates of the sediment concentration in the river. Generally, sediment discharge is expressed in terms of concentration as mg/L (ppm) or load as ton/day. In most of the cases, we observe the coefficient of determination (R^2) to check whether our data has fitted to the equation or not. If we convert the concentration values directly to the daily load values, the discharge and load is statistically auto correlated as the load term is calculated by using discharge value (Load = Concentration x Discharge) which increases the R^2 value. Therefore, in this study we use sediment concentration values instead of load for generating sediment rating curves to avoid auto-correlation issues. A bias correction factor (s^2) which is closely related to standard deviation of logarithmic concentration is used to reduce the statistical underestimation by rating curve of power line [2]. It is given by Equation 5:

$$s^2 = \sum_{i=1}^{n} \left(\log C_i - \log \hat{C}_i\right)^2 / (n-2) \tag{5}$$

Bias Correction factor = $e^{(2.65 s^2)}$. Where, C_i is Concentration of each period and $\hat{C}$ is mean of observed concentration.

[10] also suggested another method of removing statistical bias by smearing effect represented in Equation 6.

$$Q_s = EaQ^b \tag{6}$$

Where, Q_s is Sediment Concentration, E is Bias Correction factor, Q is River Discharge, a and b are the parameters of power line.

$E = \frac{1}{N} \sum_{i=N}^{N} \exp^{\ln Q_{si}(obs) - \ln(aQ^b)}$.

N is number of observations.

Optimization/Morris method mentioned in [20] is a different procedure for generating the rating curve relationship. Using the difference in total sediment load from observed and estimated values over a period as an objective function and minimizing it, leads to other sets of parameters (a and b). As the objective function has multiple local minima and doesn't poses any unique solution, it is difficult to judge the starting point of the parameters. The descent of the parameters towards local minima depends upon the initial values. So, the sediment rating power relation's parameters (a and b) from OLS are initially used as the spelling point for the rating curve generation. The objective function used for correction of parameter is given in Equation 7.

$$\sum_{i=1}^{N} \left[Q_i \times C_i \times \frac{(t_{i+1} - t_i)}{2} + Q_{i+1} \times C_{i+1} \times \frac{(t_{i+1} - t_i)}{2} \right] = \sum_{i=1}^{N} \left[Q_i \times aQ^b \times \frac{(t_{i+1} - t_i)}{2} + Q_{i+1} \times aQ^b \times \frac{(t_{i+1} - t_i)}{2} \right] \tag{7}$$

Where, Q_i is River Discharge for time i, Q_{i+1} is River Discharge for time i+1, C_i is concentration of suspended sediment for time i, $Ci + 1$ is concentration of suspended sediment for time i+1, a and b are fitting parameters. Q is in m^3/s

3. Results and Discussion

In Kabeli River, around 89.3% of total sediment load gets transported in monsoon season alone. The maximum observed sediment concentration was 46137 ppm on 27 June 2012 corresponding to discharge of 162.7 m^3/s whereas, the minimum concentration of less than 1 PPM was measured on different dates during the sediment sampling period.

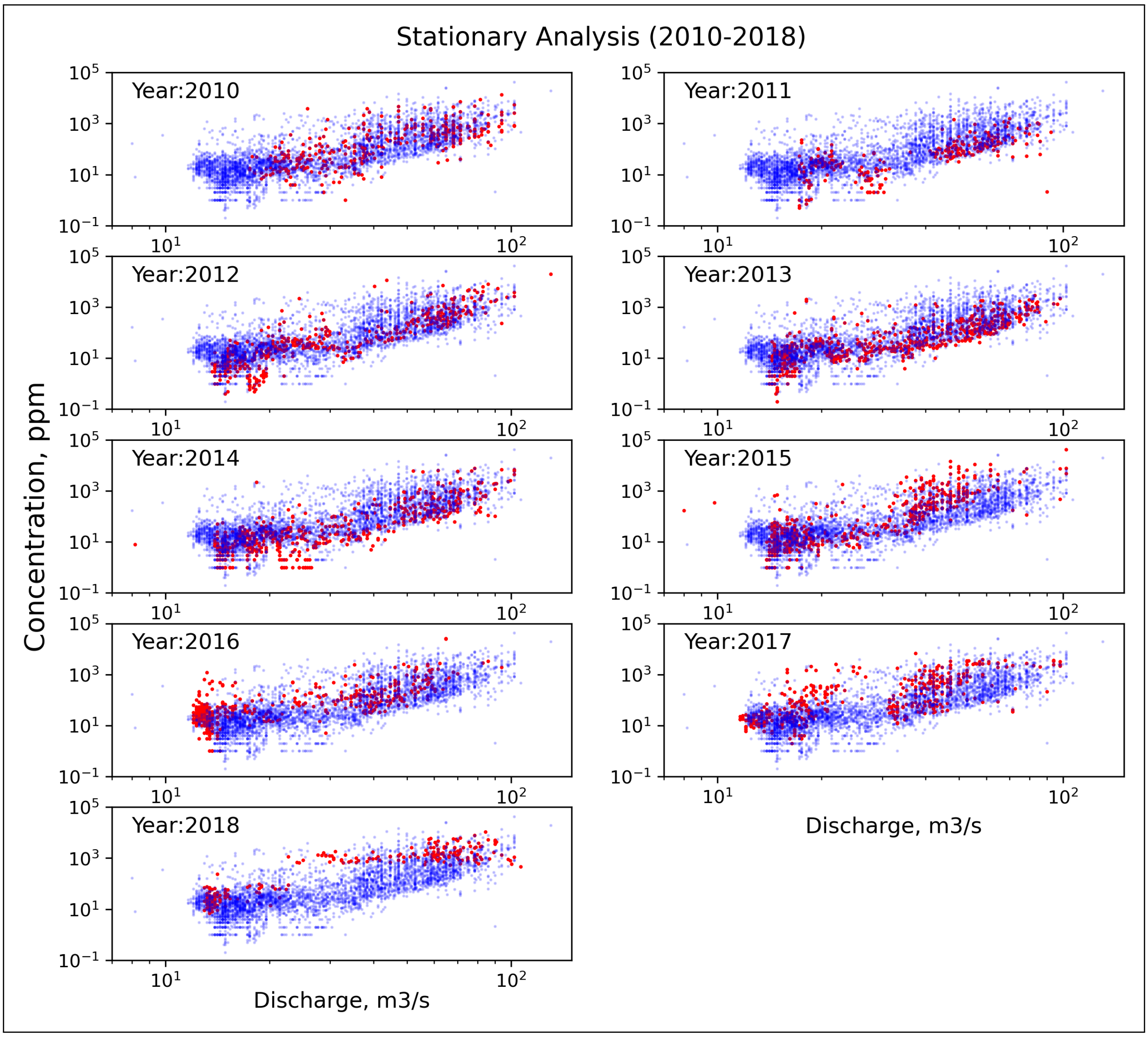

Figure 5: Year-wise (2010-2018) temporal variability of sediment concentration. Red scatter shows sediment concentration for particular year, blue scatter shows the sediment concentration for rest of the years.

Here, high variability of sediment fluxes is mostly controlled by high river discharge during monsoon season. Temporal variability of sediment fluxes (Figure 5) suggests that no peculiar or specific events have occurred over the study period in the catchment that could significantly influences the mobilization of sediment that clusters sets of sediment concentration data in certain region only.

While comparing rating curves generated using the sediment concentration and the load, coefficient of determination (R^2) value automatically increases from 0.57 to 0.71. However, overall analysis should consider the rating curve that is capable to actually capture the total sediment load rather than the one which provides false impression of the statistical parameter.

Table 2: Rating curve equations from different methods

Method	Rating Curve Equation	Under/Over Estimation
OLS	$SSC = 0.0118\ Q^{2.53}$	-54%
Duan	$SSC = 0.028\ Q^{2.53}$	8%
Ferguson	$SSC = 0.0270\ Q^{2.53}$	5.2%
Optimization	$SSC = 0.4142\ Q^{1.86}$	0%

The rating curve obtained from different methods are illustrated and tabulated in Figure 6 and Table 2 respectively. Generally, sediment rating curves are plotted in log-log graph as it has large slopes at low discharges and smaller slopes at high discharges. For

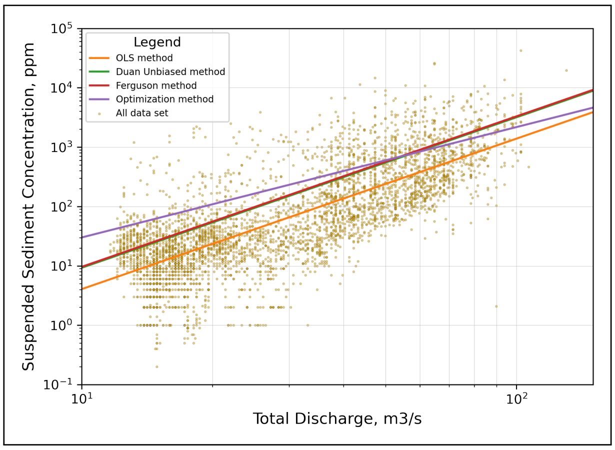

Figure 6: Sediment rating curve in log-log scale from different methods. Line representing Duan and Ferguson Methods are overlapped

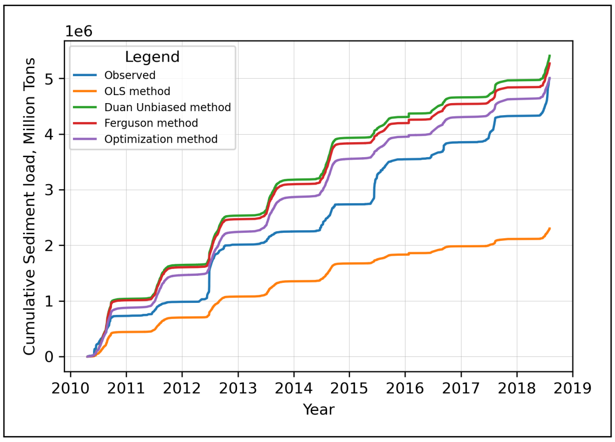

Figure 7: Plot of observed and estimated cumulative sediment load (8yr) by different methods (Time series)

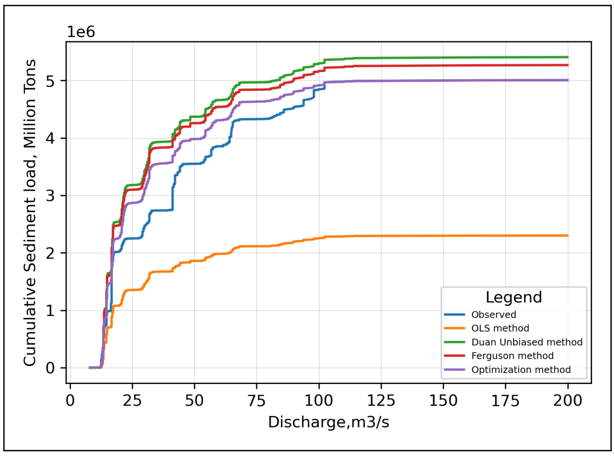

Figure 8: : Plot of observed and estimated cumulative sediment load (8yr) by different methods with respect to increasing discharge. The OLS method only able to estimate 54 % of the observed load

very high discharge, the slope of the sediment rating curve approaches to unity, which means a constant sediment concentration at various magnitude of discharges. This constant sediment concentration at high discharges is called ultimate sediment concentration [17]. This tendency is observed due to transition of nature of sediment transport from transport limited to supply limited characteristics in a catchment. In case of Kabeli River, suspended sediment concentration is found to constantly increase with increasing discharge without flattening (inflected curve) (Figure 6). It indicates that the sediment is always supply limited. This is ascribed by the high gradient of the river having great transport capability. Likewise, there were limitations in the observed ultimate sediment concentrations as the river had not experienced a major flood/rainfall event within the study period. The scatterings of the observed sediment concentration clearly indicates that there is no such equation which can accurately estimate sediment concentration for any single event.

Comparative study between observed and estimated total sediment load obtained from various methods are shown in Figure 7 and Figure 8. The abrupt increase in cumulative sediment load curve forming a ladder like pattern in Figure 8 is due to high sediment flux during monsoon season. Here, the ordinary least square could only capture 54% of the total observed load considering the whole study period. Although all of the other methods were able to capture the sediment load successfully, optimization method has obtained the closest value to the observed load ascribed by objective function used. The method suggested by [10] and [2] overlapped each other (Figure 6) due to almost same magnitude of bias correction factor and both of the methods have fairly overestimated total sediment load throughout the study period by 8% and 5.2% respectively. Except OLS, all of the corrected methods fairly overestimated total sediment load between years 2013 to 2017.

There is no uniformity of delivery of sediment load in the river over the years which can be illustrated in Table 3. The sediments generated by landslide associated with large earthquake is also a potential source of sediment [22]. Year 2015 has a significant rise in sediment load (Figure 7) which could be due to construction activities of various water-resources project within the study area and needs further investigations.

Table 3: Yearly Sediment load from different rating curve methods

Year	Sediment Yield				
	Observed	OLS	Duan	Ferguson	Morris
2010	73.17	44.13	103.71	101.06	87.58
2011	25.37	25.95	60.97	59.42	58.75
2012	102.71	37.73	88.66	86.40	77.62
2013	23.76	27.51	64.64	62.99	62.74
2014	48.74	31.99	75.18	73.26	68.64
2015	81.02	15.96	37.50	36.55	39.80
2016	30.61	14.98	35.20	34.30	35.32
2017	47.29	13.11	30.82	30.03	32.53
2018	67.87	18.71	43.98	42.86	37.58

4. Conclusions

This study has presented that sediment rating equation provided by various researchers that involves bias correction and optimization are suitable for adaptation. Although, OLS method for sediment rating is not desirable due to significant underestimation of sediment load (54% in our case).

These rating curves are site specific and should be used carefully as it needs long term data (at least throughout the year where influence of all seasons are included) to develop a curve that will fit and have acceptable results. These correction methods do not refine the parameters physically but rather involves statistical improvement either by bias correction or equivalency.

The inherent problem of scatterings of sediment rating can be reduced by correction measures but not completely eliminated. Likewise, the error of underestimation is reduced but good estimation of intra and inter seasonal sediment fluxes cannot be achieved by the sediment rating curve alone. A high degree of scattering occurs when processes involved in mobilization and transportation of sediment in the catchment do not correlate well with the river discharge. The use of soil erosion models would better predict sediment yield. Similarly, least scatter curve can also be generated by incorporating other hydraulic and hydrologic parameters like base-flow, velocity, slope, depth, stream power and precipitation [23] which has not been envisaged in this study.

Sediment rating curve of Kabeli River suggests that the sediment transport process is always in supply limited condition irrespective of discharge variation.

Bed load are difficult to measure [1] but comprises about 30% of the total river load in high mountains [3]. However, this study does not incorporate analysis of bed load factor which could be major portion of sediment load.

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References

[1] Robert R Holmes. Measurement of Bedload Transport in Sand-Bed Rivers: A Look at Two Indirect Sampling Methods.

[2] R. I. Ferguson. River Loads Underestimated by Rating Curves. *Water Resources Research*, 22(1):74–76, jan 1986.

[3] Simon J. Dadson, Niels Hovius, Hongey Chen, W. Brian Dade, Meng Long Hsieh, Sean D. Willett, Jyr Ching Hu, Ming Jame Horng, Meng Chiang Chen, Colin P. Stark, Dimitri Lague, and Jiun Chuan Lin. Links between erosion, runoff variability and seismicity in the Taiwan orogen. *Nature*, 426(6967):648–651, dec 2003.

[4] Jiahua Morris, G. L., Fan. Reservoir Sedimentation Handbook. *Aging*, 1998.

[5] Sanjay a Burele, Nayan Sharma, Z Ahmad, and Ishwer D Gupta. Numerical Simulation-Optimization for Channelization of River Kosi. *International Journal of Scientific Engineering and Technology*, 1155(3):1149–1155, 2014.

[6] Aastha Chhetri, Rijan B. Kayastha, and Ahuti Shrestha. Assessment of Sediment Load of Langtang River in Rasuwa District, Nepal. *Journal of Water Resource and Protection*, 08(01):84–92, 2016.

[7] Mukesh Raj Kafle. Sediment Transport Measurement in the Koshi River: Comparison Between Historic and Recent Measurement Results. *American Journal of Water Science and Engineering*, 5(3):111, 2019.

[8] N. E.M. Asselman. Fitting and interpretation of sediment rating curves. *Journal of Hydrology*, 234(3-4):228–248, jul 2000.

[9] D E Walling. Limitations of the rating curve technique for estimating suspended sediment loads, with particular reference to British rivers. pages 34–48, Wallingford,122, 1977. IAHS publication.

[10] Naihua Duan. Smearing estimate: A nonparametric retransformation method. *Journal of the American Statistical Association*, 78(383):605–610, 1983.

[11] B.N. Upreti, S.M Rai, and D.R. Koirala. Early Proterozoic granite of the Taplejung Window, far eastern Lesser Nepal Himalaya. *Nepal Geological Society*, 28:9–18, 2003.

[12] Hydrolab. Suspended Sediment Sampling and Laboratory Analysis for Kabeli 'A' Hydroelectric Project. Technical report, Pulchowk, Lalitpur, 2018.

[13] A.J. Horowitz. Monitoring suspended sediment and associated trace element and nutrient fluxes in large river basins in the USA, 2004.

[14] Preksedis M. Ndomba, Felix W. Mtalo, and Ånund Killingtveit. Developing an excellent sediment rating curve from one hydrological year sampling programme data. *Journal of Urban and Environmental Engineering*, 2:21–27, 2008.

[15] Douglas Glysson. Sediment-Transport Curves. Technical report, 1987.

[16] John R Gray and Francisco J M Simões. Estimating Sediment Discharge. Technical report, 2008.

[17] Victor Miguel Ponce. Ultimate Sediment Concentration. pages 311–315, Colorado, aug 1988. National Conference on Hydraulic Engineering, Colorado Springs.

[18] Nikolaos Efthimiou. The role of sediment rating curve development methodology on river load modeling. *Environmental Monitoring and Assessment*, 191(2), feb 2019.

[19] Barbara E. Peters-Kümmerly. Untersuchungen über Zusammensetzung und Transport von Schwebstoffen n einigen Schweizer Flüssen. *Geographica Helvetica*, 28(3):137–151, 1973.

[20] George Annandale, Gregory Morris, and Pravin Karki. *Extending the Life of Reservoirs*. 2016.

[21] R. I. Ferguson. Accuracy and precision of methods for estimating river loads. *Earth Surface Processes and Landforms*, 12(1):95–104, 1987.

[22] Kevin Roback, Marin K. Clark, A. Joshua West, Dimitrios Zekkos, Gen Li, Sean F. Gallen, Deepak Chamlagain, and Jonathan W. Godt. The size, distribution, and mobility of landslides caused by the 2015 Mw7.8 Gorkha earthquake, Nepal. *Geomorphology*, 301:121–138, jan 2018.

[23] Christoff Andermann, Alain Crave, Richard Gloaguen, Philippe Davy, and Stéphane Bonnet. Connecting source and transport: Suspended sediments in the Nepal Himalayas. *Earth and Planetary Science Letters*, 351-352:158–170, oct 2012.