Prediction of Sediment Inflow in Reservoirs

Balkrishna S. Chavan, Hradaya Prakash

Abstract-**Sediment in hydraulic flow plays significant role because of complexity of its bed and the flow from multi direction with the variation of its forces. Accretion and erosion at river bed, banks, dams and power intake structures are caused due to sediment transport gradient in the flow or otherwise. Therefore prediction of sediment transport is much significant for the sustainable functioning of the structure and planning of the canals training works, reservoir intakes and capacity sustenance. Sediment transport pattern in the Himalayan River is complex and sediment sampling in these rivers are often difficult. Sediment load in the river varies spatially as well as temporarily. For the Himalayan Rivers, reliable and consistent sediment rating equations are rare. The change in the flow rate and sediment concentration is very rapid and unpredictable. This research paper describes prediction of sediment inflow based on the published data. Empirical equations in mathematical form are proposed based on the data sample of 1312 observations.**

Keywords: **concentration, reservoir, sedimentation, structures**,

I. INTRODUCTION

The problem related to hydropower projects is loss of the reservoir utility due to sedimentation. Other than reservoir sedimentation, the suspended sediment also has an adverse effect on the lifespan of the blade of the turbine in a hydropower plant, which reduces the efficiency of the turbine and hence reduces electricity generation. Most of the hydropower potential is in the Himalayan region. Sediments are basically fragments of rocks and minerals that come from the weathering of rock. When the rain falls, materials are dislodged and these materials are transported on the land surface, streams and rivers act as passage for the movement of sediments. When there is not enough energy to transport the sediments, deposition occurs (Larry, W., 1999)[7]. Rivers and streams carry sediment as they flow depending on the sediment supply along their course. Depending on the settling velocity, drag and lift force, these sediments are carried along the river in either suspended form or bed-load. The bed load and suspended load are calculated using the formulae developed for alluvial rivers and the results were similar to the estimated load from the gauging station. Sediment load depends upon surface run off, which in turn depends upon rainfall.

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Sediments are transported during the monsoon months which account for about 90% of the total load transported in a year.

The object of this paper is to

- Present information on factors affecting sediment transport and about sediment transport in the other Himalayan region
- Increase the understanding of sediment transport mechanism in the reservoir,
- Present the sediment transport information and
- Finally, the information from the sediment data is to be correlated to the factors affecting the sediment transport pattern and compared to other Himalayan region.

II. FACTORS AFFECTING SEDIMENT TRANSPORT

Factors affecting sediment transport can be broadly classified as:

A. Hydrology and Climate*:* Sediment load is dependent on the river discharge. Other than discharge, variables like rainfall and snow melt also contributes to the sediment load. The river discharge is dependent on the rainfall. Discharge of the river does not necessarily indicate proportionate sediment load. From the suspended sediment discharge, a large variation in the sediment yield is observed in various rivers around the world.

B. Topography*:* With the change in topography from the tributaries of the rivers to the downstream reach of the river, the river flow changes. The velocity of flow in the river is greatly influenced by the slope of the river bed. Sediment transport depends on the flow rate and hence topography influences the sediment transport. Because of the steep topography in mountainous region, soil erosion is a naturally happening process. Soil erosion has a significant influence on the sediment load in the Mountain Rivers. Sediment is contributed to the reservoir, headwork of the major rivers by melt water issuing from glaciers, by processes such as mass movement and mud flow, by debris torrents, and by channel erosion during catastrophic outburst floods from landslide, glacier dammed lakes. Although storage in the river bed and flood plain interacts with sediment transport, upper parts of a basin greatly influence water quality downstream.

C. Geology*:* The effect of rock structure on mechanical erosion rate is probably high with respect to river bed erosion, but less important with respect to hill slope erosion because the outcropping rock structures are normally covered by soils.

River flowing over crystalline terrains erode with difficulty, whereas unconsolidated sedimentary rocks yield greater sediment loads to rivers. The Ganga-Brahmaputra Rivers carry huge sediment loads because they flow over easily erodible carbonates and through the Himalayan terrains. (Chakrapani, 2005)[3]. The area of Mountain River Basin comprises the northern part of the country.

D. Land Use: Natural vegetation has a regulating influence on runoff. Deforestation and urbanization increase the danger of flood inundation but also promote erosion. In the case of sediment yield values 310 times higher, compared to the original magnitude, were observed in small areas. Although these phenomena have long been known, no readily transferable quantitative relations do exist for predicting effects of land use change on discharge and sediment yield. The relationship between erosion occurring on-site and sediment load at a point in a stream is expressed as sediment delivery ratio for the catchment. Sediment delivery ratio is the ratio of sediment yield of a drainage basin to the total amount of sediment moved by sheet erosion and river bed erosion. Most of the sediment loads in the lower reaches of the Mountain Rivers are from materials being taken out of storages and from river erosion. Hence, there would be little change in sediment in the lower reaches of the river for large river basins for decades even if land conservation activities could inhibit all human caused, accelerated erosion in the hills. For flood and sedimentation problems in the Himalaya, human activity has less impact on the sediment load than natural factors (Lawrence, 1987)[8]. The factors affecting sediment transport were studied in detail by Garde and Kothyari (1986)[4][13] and formulated the following equations:

$$V_s = 0.02P^{0.60}F_e^{1.7}\bar{S}^{0.25}D_d^{0.10}\left(\frac{P_{max}}{P}\right)^{0.19} \quad (1)$$

$$F_e = \frac{1}{a}[0.80a_A + 0.60a_G + 0.30a_F + 0.10a_W]$$

where

- V_s = annual sediment yield in cm of absolute volume
- $\bar{S}$ = average slope of the catchment
- p = average annual precipitation in cm
- D_d = drainage density per km
- F_e = erosion factor
- a = total catchment area
- a_A = arable area
- a_G = grassland area
- a_F = forest area
- a_W = wasteland area

III. PRESENT SCENARIO OF SEDIMENT TRANSPORT STUDIES IN INDIA:

Sediment transport influences many situations that are of importance to mankind. Silt deposition reduces the reservoir capacity and modifies the path of water courses. In rivers, sediment movements form a part of the long term pattern of geological processes. Sediment transport may be understood as occurring in one of the two modes:

- By rolling or sliding along the floor/bed of the rivers; sediment thus transported constitutes the bed load.
- By suspension in the moving fluid (finer particles) which is the suspended load.

The sediment supply and transport in the Himalayas is quite significant and is considered to be highest in the world. Sediments transported globally to the oceans are estimated at about 15– 20×10^9 tonnes per year (UNEP, 2003)[18]. Due to the high rate of sediment production in the Himalayan region, Southeast Asia contributes approximately half of the sediment discharge to the oceans (Singh et.al. 2006)[15] and 20% of the global sediment input is contributed by the rivers originating from the Himalaya (Milliman and Meade, 1983)[11].

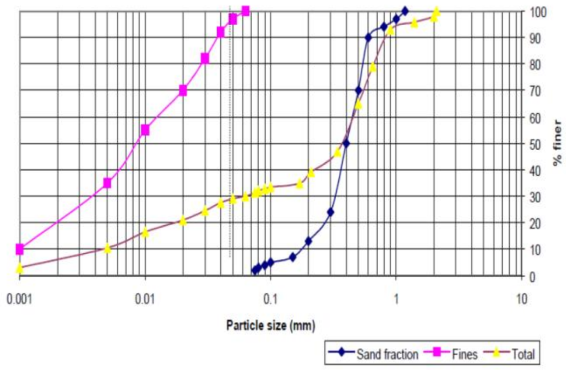

Fig.1: Particle Size Distribution

The Ganga River in India transports about 729×10^6 tonnes of sediments annually to the Bay of Bengal, 95% of which is transported during monsoon. After joining the Brahmaputra River, the total estimated combined sediment flow to the Bay of Bengal is 1620×10^6 tonnes annually. (Singh et.al. 2006)[15]. Particle size distribution pertaining to present study is shown in following Fig. 1.

Formulation of Sedimentation

Almost all bed-load formulae are one of three types in which the sediment transport rate per unit channel width (q_B) is related to either

(i) excess shear stress- according to Du Boys (1879) as referred by (Leliavsky 1954)[9]

$$(\tau_0 - \tau_{cr}), q_B = \frac{\gamma_s \Delta h \Delta U \tau_0(\tau_0 - \tau_{cr})}{2\tau_{cr}^2} \quad (2)$$

(ii) excess discharge per unit width- according to Scholitsch A. as referred by (Shulits S. 1935)[14]

$$q_B = \frac{A\, S^{\frac{3}{2}}(q - q_c)}{d^{\frac{1}{2}}} \quad (3)$$

(ii) excess stream power per unit width- according to Bagnold (1956)[2]

(iii)
$$\frac{q_B}{\gamma_s d\sqrt{\left(\frac{\gamma_s}{\gamma_f} - 1\right) d\cos\theta}} = AB_b\left\{\frac{\tau_0}{(\gamma_s - \gamma_f) d\cos\theta} - \frac{\tau_{cr}}{(\gamma_s - \gamma_f) d\cos\theta}\right\}\left\{\frac{\tau_0}{(\gamma_s - \gamma_f) d\cos\theta}\right\}^{\frac{1}{2}} \quad (4)$$

where θ is inclination of the bed with horizontal, A= 9.0 and B_b is given by

$$B_b = \frac{\sqrt{\frac{2\tan\emptyset}{3C_D}}}{\left(1 - \frac{\tan\theta}{\tan\emptyset}\right)} \approx \sqrt{\frac{2\tan\emptyset}{3C_D}}$$

A. ***Sonam Method:*** The available data shows the discharge in the mountain river varies from 40 to 1560 m^3 /s. The sediment concentration varies from fresh water to 1000 ppm. The equation derived by Sonam (2009)[16] based on published data is given below

$$C = 0.2512Q + 9.6707 \quad (5)$$

The correlation (R^2) value between sediment concentration and river discharge with the help of above equation was of 0.8. The correlation of average discharge and concentration over the record was from 0.13 to 0.53.

B. Camenen and Larson (2007)

$$\Phi = 12\,\theta^{3/2}\,e^{(-4.5(\theta_{cr}/\theta))} \quad (6)$$

where

$$\Phi = \frac{q_b}{\sqrt{[g(s-1)d^3]}}$$

$$\theta = \frac{\tau_0}{\rho g(s-1)d}$$

$$\tau_0 = \rho C_D \bar{U}^2$$

$$C_D = \left[\frac{k}{1+\ln\left(\frac{z_0}{h}\right)}\right]^2$$

k= Von Karman's constant =0.4

k_s= 2.5d_{50}

z_0= k_s/30

Where:

θ = Shield's parameter

θ_{cr} = Critical Shield's parameter

Φ = Dimensionless transport number

q_b = Volumetric bed-load transport rate per unit width

g = acceleration due to gravity

ρ = density of water

s = ratio of densities of sediment and water

d = grain diameter

C_D = total drag coefficient

τ_0 = Bed shear stress

$\bar{U}$ = Depth averaged velocity

C. Engelund and Hansen formula

$$S_t = \frac{0.05UC\tau_c^2\{1+0.5\left(\xi\frac{U_b}{U}\right)^2\}^2}{\rho^2 g^{\frac{5}{2}}\Delta\rho_S^2 d_{50}} \quad (7)$$

where

C = Chezy's coefficient

ξ = a coefficient

τ_c = Bed shear stress due to current, N/m^2

U_b = Amplitude of orbital velocity at the bed

d_{50} = Grain diameter

D. Ackers and White's (1973)[1] Method

$$\left(\frac{u_*}{U}\right)^{C_1}\frac{\gamma_f C_T D}{\gamma_s d} = C_2\left[\frac{F_1}{C_3} - 1\right]^{C_4} \quad (8)$$

where

$$F_1 = \left[\frac{u_*^{C_1}}{\sqrt{\frac{\Delta\gamma_s d}{\rho_f}}}\right]\left[\frac{U}{\sqrt{32\log\left(\frac{10D}{d}\right)}}\right]^{1-C_1}$$

$$d_* = \frac{d}{\left[\frac{\rho_f v^2}{\Delta\gamma_s}\right]^{\frac{1}{3}}}$$

a. For 1.0<d_*<60

$$C_1 = 1.0 - 0.56\log d_*$$

$$\log C_2 = 2.86\log d_* - (\log d_*)^2 - 3.53$$

$$C_3 = \left[\left(\frac{0.23}{d_*^{\frac{1}{2}}}\right) + 0.14\right]$$

$$C_4 = \left[\left(\frac{9.66}{d_*}\right) + 1.34\right]$$

b. For d_*>60

$$C_1 = 0.0, C_2 = 0.025, C_3 = 0.17 \; and \; C_4 = 1.50$$

E. Meyer-Peter and Muller(1948)[10]

$$\Phi = 8(\theta - \theta_{cr})^{3/2} \quad (9)$$

F. Nielsen(2000)[12]

$$\Phi = 12\,\theta^{1/2}\,(\theta - \theta_{cr}) \quad (10)$$

Table:1. Prediction of Sediment by Investigators

S No.	Investigators	Predicted Sediment ton
1	Sonam Method	12956919.10
2.	Camenen and Larson Method	1194604.32
3.	Engelund and Hansen Method	756025.46
4.	Ackers and White's Method	600278.89
5.	Meyer-Peter and Muller Method	445292.83
6.	Neilsen Method	210378.91
7.	Observed	119607.29

IV. PRESENT STUDIES

Present studies describe prediction of sediment inflow based on the published data. The catchment area of the basin is 6271 square kilometer. Width of the river at gauging station is 71.4 m. Empirical equation in mathematical form is proposed based on the data sample of 1312 observations.

$$R^2 = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum\sqrt{(x-\bar{x})^2(y-\bar{y})^2}}$$

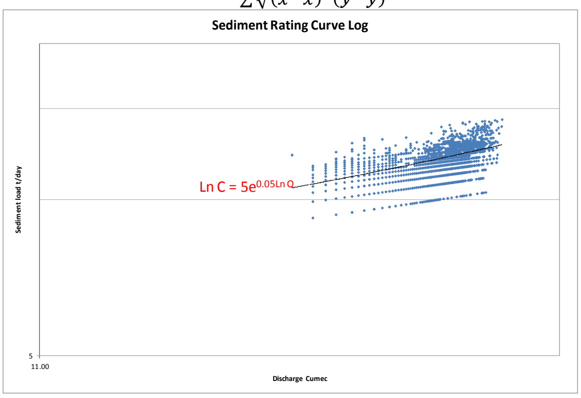

Fig. 2: Variation of Sediment Concentration and discharge (Log plot)

This linear regression equation does not cover the whole data.

$$Ln\ (C) = 5e^{0.05(LnQ)} \quad (11)$$

The Correlation coefficient R^2 for the equation (11) is 0.96, which is shown in Fig. 2. This empirical equation does not cover majority of data.

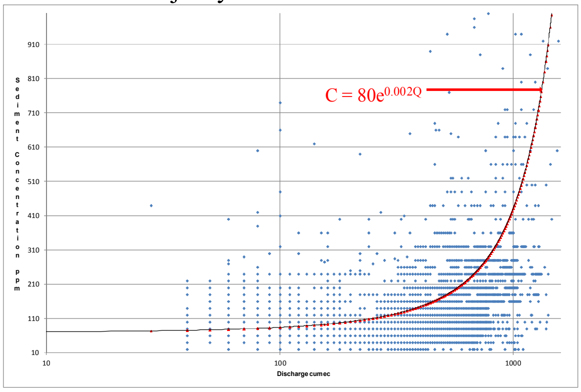

Fig. 3: Variation of Sediment Concentration and discharge (Semi-log)

$$C = 80e^{0.002Q} \quad (12)$$

The best fit curve for equation (12) is shown in Fig. 3. This equation predicts well sedimentation for the discharge ranging from 100 to 1000 m^3/s.

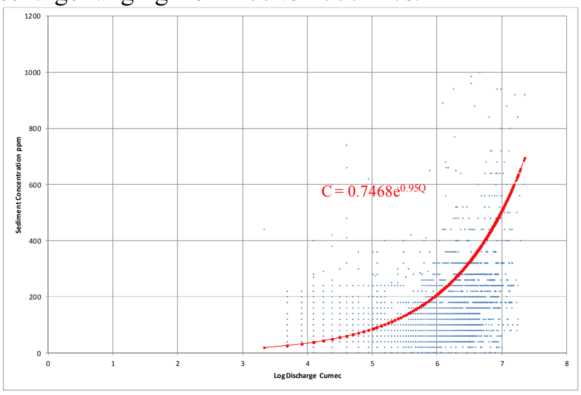

Fig. 4: Variation of Sediment Concentration and Discharge

$$C = 0.7468e^{0.95Q} \quad (13)$$

The best fit curve for equation (13) is shown in Fig. 4. This empirical exponential equation estimates quantum of sedimentation better than equation number 12.

Equations proposed above are difficult to use. Therefore the data was re-analyzed and simple quadratic equation as below is proposed:

$$C = 0.0005Q^2 - 0.2Q + 125 \quad (14)$$

The proposed equation (14) envelops 94 % of the sediment data at one hundred percent band width, it is also seen that 63% of the sediment data at fifty percent band width, which is shown in Fig. 5.

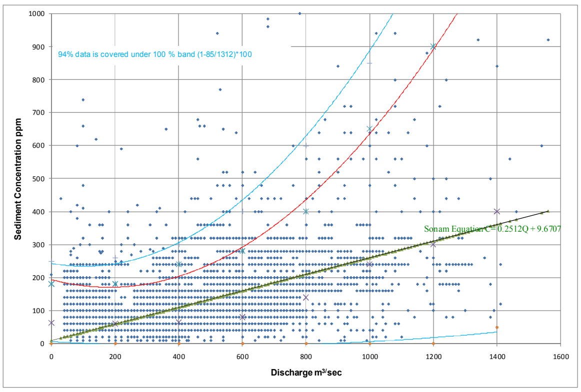

Fig. 5: Variation of Sediment Concentration and Discharge

A. *Data Analysis and Discussion:*

The bed load in present study is assumed as 30% Sonam (2009)[16]. Sediment concentration plays significant role in prediction of sedimentation in the reservoirs. Actual sediment deposited in the reservoir per annum is always varying.

Table: 2. Prediction of Sediment

S No.	Investigators	Predicted Sediment ton
Present Studies		
1.	Semi-log $80e^{0.002Q}$ Method	409805.58
2.	LogC- LogQ Values $0.7468e^{0.95Q}$ Method	366726.49
3.	Quadratic $0.0004Q^2 - 0.0025Q + 90$ Method	342617.84
4.	Log-log plot $5e^{0.05\ \ln Q}$ Method	316959.32
5.	Observed	119607.29

Actual sediment deposited in the reservoir and the prediction of sediment by different investigators is tabulated in table 2.

B. *Discharge Calculation:*

Grishanin(1967) [5] [6] conducted studies for 25 sites on 21 rivers and suggested an equation for the discharge known as Universal Stage Discharge Relation as given below:

$$Q = 14.863W^{0.5}D^{1.766}d_{50}^{0.234} \quad (15)$$

Above equation (15) is used with appropriate constant to predict the discharge as shown in Fig.6.

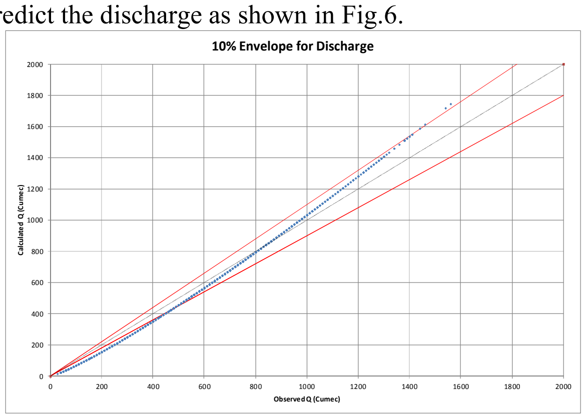

Fig. 6: Universal Stage Discharge variation

V. CONCLUSIONS

Sediment concentration varies largely with time and a major bulk of the annual sediment load is transported within a few monsoon days. Systematic efforts are made to predict the sediment in the reservoir.

- From table 1 it can be seen that methods utilized in the Europe to predict the sediment inflow are not applicable for Himalayan Rivers.
- Empirical equation (11) shows the prediction for smaller discharges are well within 3%, whereas for the higher discharges it envelops 95% data. The predicted sedimentation is close to the observed quantity.
- The quadratic equation (14) envelops 94 % of the sediment data at one hundred percent band width, it is also seen that 63% of the sediment data at fifty percent band width. It can be concluded that prediction of sediment for the discharge up to 1200 cumec is well within 5 % error.
- There is wide variation in the predicted and observed sedimentation from tables, it can be concluded that the estimated sedimentation by the present studies are limited to a specific region, therefore, required to verify with different methods.

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