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Sediment transport predictor in the Ganges river

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Abstract

In this study, the unit stream power formula and modified unit stream power formula have been applied for the estimation of sediment transport in the Ganges river. The modified unit stream power function is applicable to high concentration of fine sediment. The annual variation in the percent of fine suspended discharge shows that the Ganges river at Hardinge bridge contains a substantial amount of wash load. Based on observed data, sediment transport has been computed using Yang's stream power formula and modified Yang's formula. Comparison between computed and observed sediment discharge shows that Yang's formula over-predicts the sediment transport. The discrepancy ratio and standard deviation indicate the accuracy of the sediment transport predictors. Modified Yang's formula performs better for Ganges river. The modified Yang's sediment transport formula can be used in modeling sediment load in the Ganges river. The Yang's formula can also be used after adjusting the computed sediment load by an appropriate multiplying factor.

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1. Introduction

Ability to accurately estimate sediment transport capacity is a key to the success of water resources projects. Information on sediment load is very important for the planning, design and maintenance of any water resources development projects. Knowledge of sediment load carried by a stream is necessary for the solution of most problems associated with rivers (Garde and Ranga Raju, 1985).

Sediment transport is a complex process and often subject to semi-empirical or empirical treatment. Most theoretical treatments are based on some idealized and simplified assumption that the sediment transport rate can be determined by one or two dominant variables such as water discharge, average flow velocity, energy slope, and shear stress.

A number of equations have been developed to compute the amount of sediment discharge as a function of the various flow parameters. Each equation is supported by limited laboratory data and, occasionally, by field data. The calculated results from various equations often differ drastically from each other and from the observed data. Consequently, none of the published sediment transport equations have gained universal acceptance in confidently predicting sediment transport rates, especially in rivers (Yang, 1996).

2. Background of the study

Yang (1972) demonstrated that the sediment transport rate depends on the unit stream power more than any other hydraulic parameter. The unit stream power is defined as the rate of potential energy expenditure per unit weight of water. A dimensionless unit stream power equation was obtained by Yang (1973) for the computation of total sediment concentration in the sand size range, or the total bed material concentration when wash load is significant. In order to improve the accuracy of the equation for low sediment concentration, criteria for incipient motion were developed (Yang, 1973) and used in the equation. Due to the uncertainties involved in determining the flow conditions precisely at incipient motion, Yang (1979) developed an accurate unit stream power equation for total load, or total bed material load, in the sand size range without using any criteria for incipient motion.

The unit stream power concept is not only shown to be more generally applicable based on data confirmation but also can be derived directly from basic theories in fluid mechanics and turbulence (Yang, 1996). It was shown that bed-load, suspended-load and total load concentrations are directly related to unit stream power. The generality of assumption used in the development of the unit stream power equations, the dimensionless parameters used in these equations and vast amount of data used in the calibration of the dimensionless parameters may be the basic reasons why, in general, the unit stream power equations are more accurate than others for non-cohesive materials under most laboratory and field observations. The applicability of Yang’s (1979) equations to natural rivers in the United States was tested and verified by ASCE task committee (1982). Yang et al. (1996) modified Yang’s (1979) stream power formula so that it can be applied to the estimation of sediment transport in a sediment-laden river with a high concentration of fine suspended materials.

Every year, large discharge and heavy sediment load in the monsoon cause the river Ganges to be extremely unstable. As the Ganges is a sediment-laden river, it is expected that the prediction formula might be applicable to estimation of sediment transport in the Ganges. In this study, the stream power formulae of Yang (1979) and Yang et al. (1996) have been applied for the estimation and prediction of sediment transports in the Ganges river. Because of the high sediment concentration in the Ganges river, it can be assumed that Yang et al. (1996) equation is more applicable and have been used in this study.

3. Previous studies in Bangladesh

Several studies have been carried out in the past on the application of sediment prediction formula in Bangladesh. Bari (1978) studied sediment transport prediction using data from the Ganges river at Hardinge bridge and from Jamuna at Bahadurabad. He concluded that the Colby (1957) and Engelund and Hansen (1967) formulas may be applicable with appropriate correction factors. Dey (1995) developed a schematized sediment transport predictor for study of alluvial rivers and applied it to the Jamuna river. He found that the transport predictors namely Hossain (1985), Engelund and Hansen (1967) and Bagnold (1966) formulas are found to be suitable for the application of the Jamuna river. Ahmed (1996) studied applicability of sediment transport predictors in the Jamuna river by measured shear velocity. He found that the performance of sediment transport equations improves significantly when using measured shear stress. FAP 24 (1996) developed a sediment transport equation for both Ganges at Hardinge bridge and Jamuna at Bahadurabad. The suggested dimensionless sediment transport equation for the Jamuna river was derived on the basis of observed data from the Jamuna river for 1984-87. They used an independent data set of Bangladesh Water Development Board (BWDB) for the period 1993-1994. The results indicated that the suggested equation slightly over predicts the sediment transport rate. They applied a correction factor of 0.75 to adjust this variation. A comparison of the developed equation and five selected sediment transport prediction formulas show an accuracy in the following descending order are: Suggested equation, Bagnold (1966), Engelund and Hansen (1967), Yang (1973), van Rijn (1984) and Acker and White (1973). They, however, did not compare the performance of the suggested equation with the observed data of the Ganges at Hardinge bridge due to inaccuracy of the data.

4. Derivation of Yang's unit stream power function

4.1 Evaluation of basic assumptions

With the exception of probabilistic and regression approaches, most sediment transport equations were derived on the assumption that sediment transport rate or concentration could be determined by a dominant variable such as water discharge, average flow velocity, energy or water surface slope, shear stress, stream power per unit bed area, and unit stream power. Yang (1972) used the laboratory data of Guy et al. (1966) to examine the validity of the assumptions. He found that more than one value of total sediment discharge results from the same value of water discharge, velocity, slope, or shear stress. The generality and applicability of any equation derived from one of the assumptions is therefore questionable. To overcome this, Yang (1972) introduced the concept of unit stream power.

4.2 Concept of unit stream power

Yang (1972) defines the unit stream power as the velocity (V)- slope (S) product or VS. The rate of energy per unit weight of water available for transporting water and sediment in an open channel with reach length x and total drop of Y is,

$$\frac{dY}{dt} = \frac{dx}{dt}\frac{dY}{dx} = VS \tag{1}$$

Yang argued that the rate of work being done by a unit weight of water in transporting sediment must be related to the rate of work available to a unit weight of water. Thus, the total sediment concentration or total bed-material load must be directly related to unit stream power. Yang (1972) emphasized the power available per unit weight of fluid to transport sediments.

4.3 Stream power formula

To determine total sediment concentration, Yang (1973) considered a relation between the relevant variables of the form

$$\phi\left(C_t, VS, U_*, \nu, \omega, d\right) = 0 \tag{2}$$

where, C_t = total sediment concentration, with wash load excluded (in ppm by weight), VS = unit stream power, U_* = shear velocity, ν = kinematic viscosity, ω = fall velocity of sediment, d = median particle diameter.

Yang (1979) introduced the following unit stream power equation:

$$\log C_t = 5.165 - 0.153\log\frac{\omega d}{\nu} - 0.297\log\frac{U_*}{\omega} + \left(1.780 - 0.360\log\frac{\omega d}{\nu} - 0.480\log\frac{U_*}{\omega}\right)\log\left(\frac{VS}{\omega}\right) \tag{3}$$

4.4 Non-equilibrium high concentration sediment transport

Eq. (3) was developed for sediment transport in fairly clear water without too much wash load. Before (3) can be applied to a river with high concentration of fine sediments, it is necessary to change the values of fall velocity, kinematic viscosity, and relative specific weight to reflect the situation of sediment transport in flows with high concentrations of suspended load (including wash load). The modified unit stream power formula as derived by Yang et al. (1996) for sediment-laden flows is

$$\log C_t = 5.165 - 0.153\log\frac{\omega_m d}{\nu_m} - 0.297\log\frac{U_*}{\omega_m} + \left(1.780 - 0.360\log\frac{\omega_m d}{\nu_m} - 0.480\log\frac{U_*}{\omega_m}\right)\log\left(\frac{\gamma_m}{\gamma_s - \gamma_m}\frac{VS}{\omega_m}\right) \tag{4}$$

where, γ_s is the specific weight of sediment, w_m is the particle fall velocity in a sediment laden-flow, ν_m is the kinematic viscosity of sediment-laden flow and γ_m is specific weight of sediment-laden flow.

The coefficients in Eq. (4) are identical to those in (3). However, the values of fall velocity, kinematic viscosity, and relative specific weight are modified for sediment transport in sediment-laden flows with high concentrations of fine suspended materials.

5. Data used

Discharge and sediment load data of the Ganges river at Hardinge bridge gauge station have been collected from the Directorate of Surface Water Hydrology of BWDB. The sediment data available since 1966 contains only suspended sand discharge. This means that the sample was not separated into the wash load (also called fine fraction) and suspended bed material load (also called sand fraction). The wash load consists of silt and clay fraction. The sand fraction consists of the sediment particles larger than 0.063 mm. The sediment comprises of only suspended load since BWDB does not measure any bed load on regular basis. The sediment data used for this study are for 1983 - 88 and 1992 - 94. These data are separated into the wash load and the suspended bed material load. The data on width, average flow depth, cross-sectional velocity have also been collected of BWDB. Since the data on longitudinal bed slope and water temperature are unavailable, the longitudinal slope has been obtained from the literature as 5.5x10-5 (FAP 24, 1996).

6. Sediment concentration in the Ganges river

Analysis of available data show that on an average, the percent of fine sediment discharge with respect to total sediment discharge is about 50 which means that the Ganges river at Hardinge bridge gauge station contains a substantial amount of wash loads. So the modified Yang's equation can be applied to compute sediment transport in the Ganges river.

7. Computation of sediment transport

Based on observed data, sediment transport rates have been computed using Yang's (1979) formula and modified Yang's formula (Yang et al., 1996). Figures 1 and 2 show the comparison between computed and observed sediment discharge, most of the points lie above the 45^0- line which implies that the Yang (1979) formula over-predicts the sediment transport. But in Figure 3, the points are more or less distributed along the 45^0 - line. In both figures, there are scattering of the points. The Ganges river constantly undergoes scouring and deposition. Consequently, observed sediment transport at a given time can be higher or lower that the computed values. Part of the scattering shown in Figures 1 and 2 reflect this phenomenon. Another reason for the scattering is the inaccuracy of field measurements.

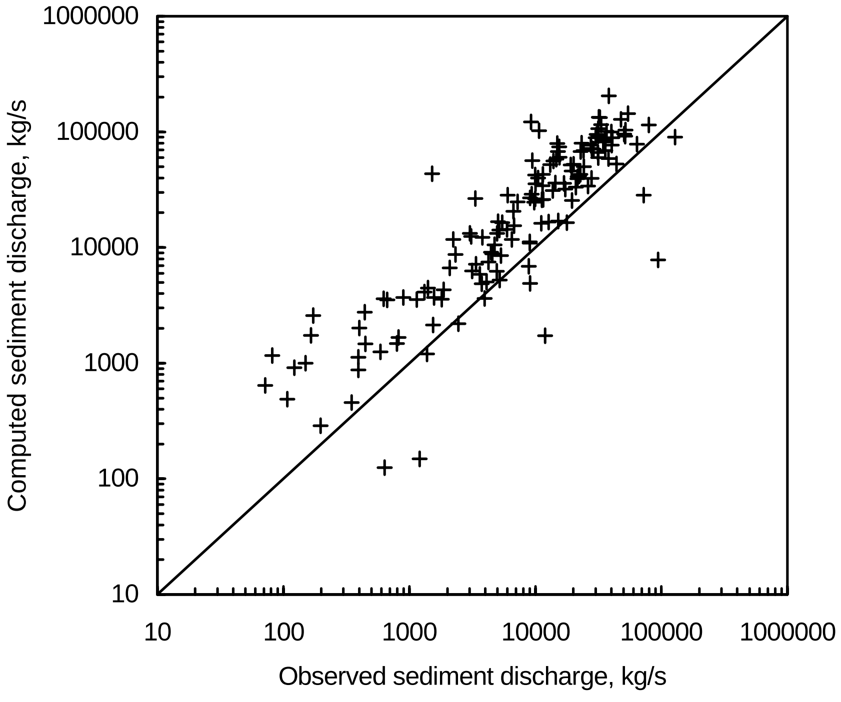

Fig. 1. Comparison between computed and observed sediment discharge based on Yang's (1979) unit stream power formula

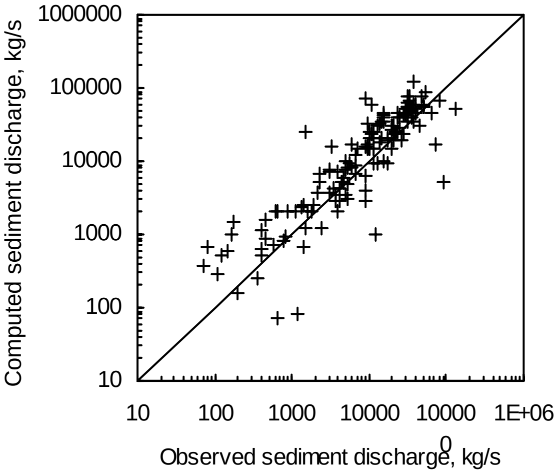

Fig. 2. Comparison between computed and observed sediment discharge based on Yang et al. (1996) unit stream power formula

Due to the uncertainty of the accuracy of measurements and the fact that flow and sediment conditions in the Ganges river cannot be maintained at true equilibrium, the scattering in Figures 3 and 4 should not be a surprise (Akhter, 2004). Another factor is the location of the gauging station on the Ganges at Hardinge bridge which is artificially narrowed down. At this point, the contraction scour of the river bed induces a yearly variation in the sediment transport which is not representative of the whole reach of the Ganges river. The sediment data collected from this constriction will not lead to good estimates of the overall sediment budget. Also, there is a bend upstream of Hardinge bridge, which again implies that this station is not well suited for sediment gauging.

If the sediment load computed by the Yang's (1979) formula is adjusted with a multiplying factor of 2, then computed and observed sediment loads match reasonably well (Fig. 3).

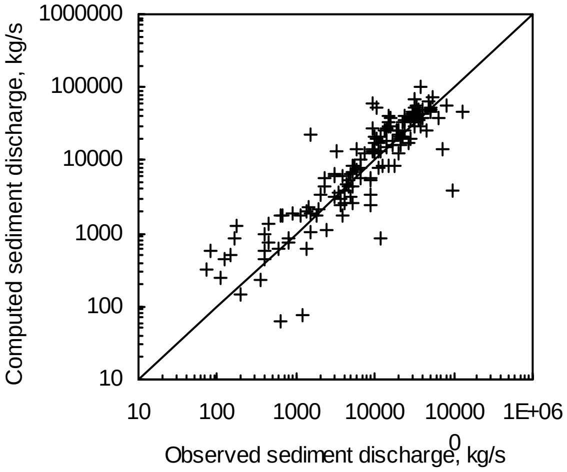

Fig. 3. Comparison between computed and observed sediment discharge based on Yang et al (1979) unit stream power formula after adjusting the computed sediment load with a multiplying factor of 2

8. Goodness-of-fit of the sediment transport predictors

The discrepancy ratio indicates the accuracy of the goodness of fit between the computed and observed data which can be expressed as

$$R_i = \frac{\psi_c}{\psi_m} \tag{5}$$

where, ψ_c = computed sediment concentration, ψ_m = measured sediment concentration. The mean value R_i and standard deviation σ of the discrepancy ratio are,

$$\overline{R} = \frac{\sum_{i=1}^{j} R_i}{j} \tag{6}$$

and

$$\sigma = \sqrt{\frac{\sum_{i=1}^{j} \left(R_i - \overline{R}\right)^2}{j}} \tag{7}$$

Another way to measure the goodness of fit is the use of average discrepancy ratio and standard deviation based on the average value of the logarithm ratio between computed and observed results using the following parameters:

$$D_i = log\left(\frac{\psi_c}{\psi_o}\right) = log\,\psi_c - log\,\psi_o \tag{8}$$

$$\overline{D}_a = \frac{\sum_{i=1}^{j} D_i}{j} \tag{9}$$

$$\sigma_a = \sqrt{\frac{\sum_{i=1}^{j} \left(D_i - \overline{D}_a\right)^2}{j-1}} \tag{10}$$

For a perfect fit, $\overline{D}_a$ = 0 and σ_a = 0.

Figure 1 shows the comparison between observed and computed sediment transports based on Yang's 1979) formula giving $\overline{R}$ = 3.210 and σ = 3.216. Figure 2 shows a similar comparison based on Yang et al. (1996) formula giving $\overline{R}$ = 1.866 and σ = 1.869. The change of mean discrepancy ratio from 3.210 to 1.866 indicates that Yang et al. (1996) unit stream power formula performs better for the sediment laden Ganges river.

Comparisons between computed and observed sediment concentrations based on the average logarithm ratio are summarized in Table 1. Yang et al. (1996) formula is more accurate based on $\overline{D}_a$ but less accurate based on σ_a when compared with Yang's (1979). The above tests for goodness of fit suggest that the modified unit stream power formula can be used as sediment transport predictor for the Ganges river. The Yang et al. (1996) sediment transport formula can be used in modeling sediment load in the Ganges river.

Applying the correction factor to the Yang's (1979) formula gives better results compared to modified Yang's formula. So the Yang's (1979) formula can also be used instead of Yang et al. (1996) formula after adjusting the computed sediment load by an appropriate multiplying factor.

Table 1
Goodness of fit test parameters for different predictors

Formula	$\overline{R}$	σ	$\overline{D}_a$	σ_a
Yang's formula (1979)	3.210	3.216	0.350	0.351
Modified Yang's formula (1996)	1.866	1.869	0.142	0.377
Yang's formula (Correction factor)	1.610	1.608	0.077	0.351

9. Conclusions

The unit stream power formula and modified unit stream power formula applicable for high concentration of fine sediments have been applied for the estimation and prediction of sediment transport in the Ganges river. Based on observed data, sediment transport rate has been computed using Yang's stream power formula and modified Yang's formula. The comparison between computed and observed sediment discharge based on Yang's formula and modified Yang's formula show that Yang's formula over predicts the sediment transport. The discrepancy ratio and standard deviation suggest that modified Yang's formula performs better for the sediment laden Ganges river. The modified Yang's sediment transport function can be used in modeling sediment load in the Ganges river. The Yang's formula can be used instead of the modified Yang's formula after adjusting the computed sediment load by an appropriate multiplying factor.

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Notation

C_t = Total bed-material concentration, excluding wash load, in parts per million by weight
C_v = Suspended sediment concentration by volume, including wash load
d = Median sediment particle diameter
D_i = Discrepancy ratio based on logarithm ratio
Da = Averaged discrepancy ratio based on logarithm ratio
R_i = Discrepancy ratio
R_i = Aaverage discrepancy ratio
j = Total number of data used
U* = Shear velocity
V = Average flow velocity
VS = Unit stream power
S = Longitudinal bed slope
ψ_c = Computed value
ψ_o = Observed value
ω, ω_m = Sediment particle fall velocity in water and sediment laden flow respectively
ν, ν_m = Kinematic viscosity of water and sediment-laden flow respectively
γ_s, γ_m = Specific weight of sediment and sediment-laden flow respectively