Prediction of total load transport of an Indian alluvial river to estimate unmeasured bed load through an alternative approach

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Predicting sediment transport in a natural stream is essential to adequately design different hydraulic structures like bridge piers, dam, causeway, etc., having a long service life. The prediction of sediment transport is a challenging task keeping in view the dynamic conditions of stream flow, which in turn depends upon a number of continuously and randomly changing flow parameters, channel parameters and fluid properties and thus no uniform mathematical or physical relationship can be adopted for prediction of sediment transport. The available empirical solutions, based mostly on regression, vary largely from one site condition to other. In India the bed load data is rarely measured and thus the availability of total load data for Indian alluvial river is virtually nonexistent and therefore a true empirical relationship cannot be developed for predicting total load in Indian streams. The present study aims to bridge this gap through a three-prong approach to predict the total load of an alluvial river (Shetrunji River). The unavailable (unmeasured) bed load data is computed using firstly, selected bed load transport equations and secondly, using Maddock's estimation. These computed total load (computed bed load plus observed suspended load) are compared with the total load transport predicted using Yang' 1973 and Yang' 1979 Unit Stream Power (USP) equations. It was found that the best prediction of total load is obtained for Yang' 1973 equation, when Shields (1936) bed load formula is used to compute bed load or when bed load is taken as 5% of observed suspended load. This methodology can be applied to predict the total load of rivers with reasonably good accuracy even in the absence of unmeasured bed load.

Keywords: Alluvial rivers, bed load, empirical relationship, sediment transport, suspended load.

MANAGING alluvial river systems requires knowledge of the total load transport[1]. Information regarding bed load is important to find total load in the stream, which is the sum of primarily bed load and suspended load. Different formulae for estimating sediment transport rate for different loads such as bed load, suspended load and total load are provided in the literature. Bed load transport rate has also been computed for different sediment conditions, such as uniform bed load, non-uniform bed load or the fractional transport rate of non-uniform bed load. Several researchers have developed models for finding uniform and non-uniform bed load transport rate[2–8]. Several bed load models have been developed for computing the fractional transport rate of non-uniform bed load[9–15]. Applicability of these models is mainly for sand bed rivers. Total load transport models based on different concepts such as regime approach[16–18], regression approach[19,20], probabilistic approach[3,21,22] and stream power concepts[4,23–27] have been used to predict total sediment load. These models have been statistically assessed to check the accuracy, using paired data of measured and predicted total load transport rates. As reviewed in the literature, unit stream power (USP) is considered as a dominant factor in the determination of total sediment concentration. For the computation of total sediment concentration (for sand transport), Yang[24] developed an USP equation considering the incipient motion criteria and developed an USP equation without using any criteria for incipient motion[25]. He further developed a dimensionless USP equation for gravel transport[26]. Several researchers found that Yang's method provided a relatively accurate prediction[28–31]. Determining the unique set of flow conditions for incipient condition is difficult. A relationship for sediment transport based on incipient conditions will be volatile and needs to be calibrated frequently even for the same site. On the other hand, a relationship disregarding incipient conditions may be less accurate in prediction. The dilemma to use one of the two conditions is evident and the decision may be based on either experience or reference from similar site conditions which will again suffer from calibration issues in the absence of sufficient measured bed load data. The major drawback in the empirical analysis is that it depends on the availability of sufficient and correct measured data for a long period. It also needs contextual correlation to any major flood event. Unavailability of reliable measured bed load data for Indian alluvial rivers has made it difficult to test and employ empirical relationships for total load prediction while designing hydraulic structures. We have not come across any literature discussing the prediction of total load

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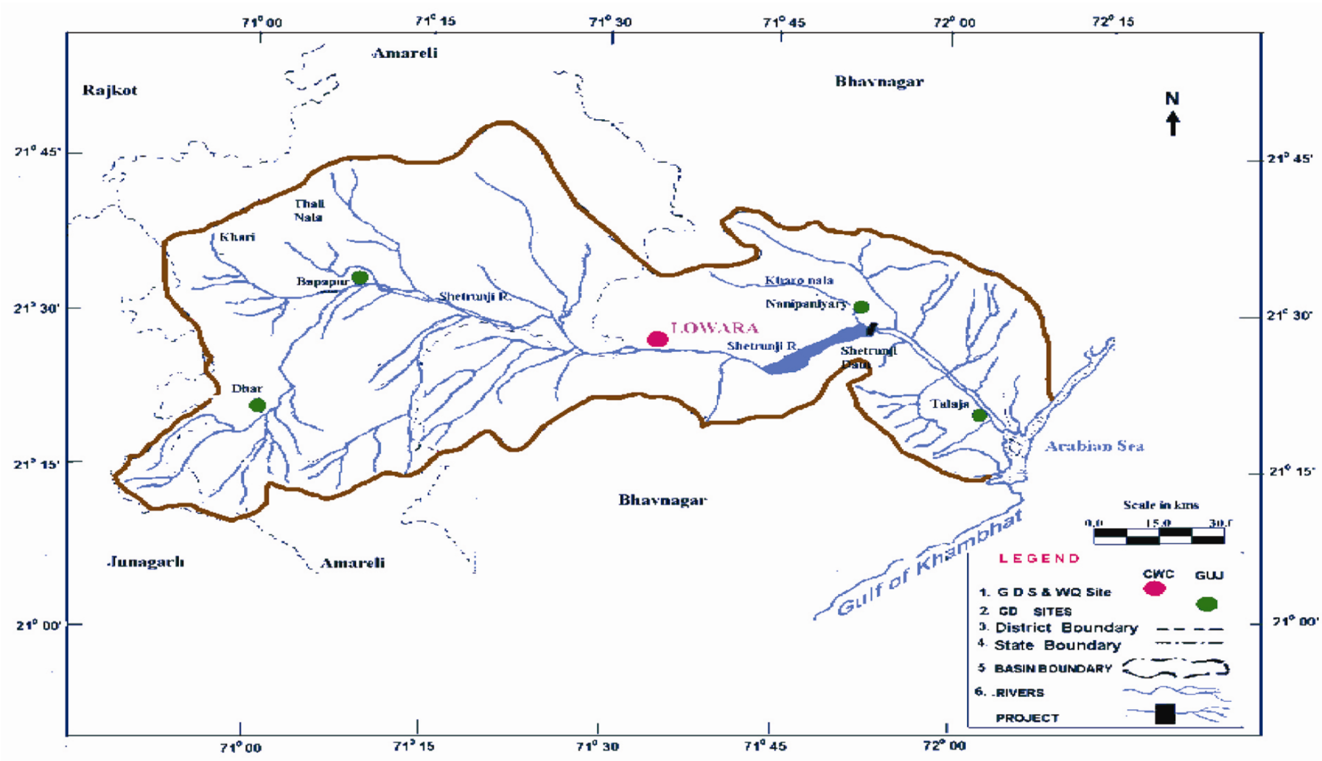

Figure 1. Shetrunji River Basin and sediment gauging station at Lowara, Gujarat, India.

transport of Indian alluvial rivers, in the absence of measured bed load. The present study aims to find the extent of variation in the results obtained using these two opposite relationships, i.e. Yang 1973 model based on incipient motion and Yang 1979 model without considering incipient motion, of predicting total load transport rate for the Shetrunji River (study area), Gujarat, India. The need to predict total sediment load transported for Shetrunji River is due to the rapid increase in the rate of siltation at the Shetrunji reservoir. The rate of siltation at Shetrunji reservoir from 2000 to 2007 was 4.29 M cum/year, which is 65% more than during the period of impoundment, i.e. 1965–2000 (2.59 M cm/year)[32]. To find the reason for the increase in sediment flow, prediction of total load transport for an alluvial river is necessary to understand the influencing parameters and for protection of the structure from high rate of siltation. High siltation can significantly reduce the service life of reservoir storage and cause scouring around bridge piers leading to high maintenance and failure of such structures. For predicting total load for Shetrunji River, in the present study, first for the unavailable measured bed load data of the river, bed load was computed using (i) uniform and non-uniform bed load equations according to existing bed material data, and (ii) Maddock's[33] approach based on sediment concentration and mean sediment size. Total sediment load of Shetrunji River has been calculated by adding bed load computed and observed suspended load (obtained from Central Water Commission (CWC)). Total sediment load was predicted for Shetrunji river using Yang[24] and Yang[25] USP equations. The predicted total load was compared with calculated total load to verify the suitability of Yang equation.

Study area and data collection

Shetrunji River is one of the major rivers flowing through the Saurashtra region in Gujarat. It originates at Chachai hill in Gir Forest of Junagadh district and meets the Arabian Sea in the Bay of Khambhat. The total length of this east-flowing river from its origin to the outfall is 182 km. The river drains an area of 5514 sq. km. The basin is situated between 70°50′ and 72°10′E long and 21°00′ and 21°47′N lat. The average annual rainfall of the basin is 604 mm. In winter, the minimum temperature varies from 6°C to 18°C. Khidiyar and Shetrunji dams are located on Shetrunji River at a distance 55 km and 160 km, with catchment areas of 384 and 4317 sq. km respectively. The river bed consists of sand, gravel and rock. The main tributaries contributing to Shetrunji river are Shel, Khari and Talaji on the right bank and Satali, Thebi, Gagario, Rajaval and Kharo on the left bank (Figure 1). The suspended sediment data were collected from CWC, Gandhinagar. The data were measured at Lowara gauging station. Table 1 gives the range of various hydraulic parameters for Shetrunji River.

Table 1. Range of hydraulic parameters for Shetrunji River

Data source	Flow discharge (l/s)	Flow depth (m)	Flow width (m)	Slope (m/m)	Median grain size (mm)	No. of data points
Shetrunji River	137–1,016,894	0.49–5.465	8–74	0.00002–0.08801	2.93–1.43	338

Approaches for predicting total load transport rate

Shetrunji River data were analysed using Yang (1973) USP sediment transport equation considering the incipient motion criteria. In this approach, the critical USP (product of critical average flow velocity and slope) is required to start the movement of sediment particles. Further, the same data were analysed using Yang (1979) approach where critical USP is not considered so as to increase applicability for a wider range of sediment size. As the sediments of Shetrunji River are in sand size range, analysis of river data was not done for Yang (1984) USP equation, which is mainly for gravel transport. A comparative analysis was done between the two selected approaches. The approaches considered in the present study are briefly explained below.

Yang (1973) USP equation

Yang[24] developed a relationship between dimensionless effective USP and total sediment concentration C_t. Further, using multiple regression analysis with 463 flume data, prediction of total sediment concentration C_t (in parts per million (ppm) by weight) for particles in the sand size range with $d_s = d_{50}$ (median sieve diameter of bed material) is made as

$$\log C_t = 5.435 - 0.286\log\left(\frac{\omega d_S}{v}\right) - 0.457\log\left(\frac{u_*}{\omega}\right) + 1.799 - 0.409\log\left(\frac{\omega d_S}{v}\right) - 0.314\log\left(\frac{u_*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_c S}{\omega}\right), \quad (1)$$

where V_c denotes the critical average flow velocity and the product ($V_c S$) indicates the critical USP required to start the movement of sediment particles, S the channel slope, V the velocity of flow, u_x the shear velocity and ω is the fall velocity of the particles.

Yang (1979) USP equation

Yang[25] also proposed a simplified equation by neglecting critical USP in eq. (1); through multiple regressions the constants are modified as given in eq. (2)

$$\log C_t = 5.165 - 0.153\log\left(\frac{\omega d_S}{v}\right) - 0.297\log\left(\frac{u_*}{\omega}\right) + 1.78 - 0.36\log\left(\frac{\omega d_S}{v}\right) - 0.48\log\left(\frac{u_*}{\omega}\right)\log\left(\frac{VS}{\omega}\right). \quad (2)$$

Methodology

The suspended load data were provided by CWC, Gandhinagar. However, bed load transport rate is required for predicting total sediment load transport rate. In the absence of measured bed load data, total load transport analysis of river data has been done using bed load prediction equation for computation of unmeasured bed load[34,35]. For the present study, in the absence of observed fractional bed material data for the collected river data, uniform and non-uniform bed load sediment transport equations have been selected for computation of bed load. Total load transport data for Shetrunji River were then generated by summation of observed suspended load and predicted bed load using two approaches.

In the first approach, bed load was computed using some of the selected bed load sediment transport equations[2,5–8] and subsequently each of these bed load values was added to the measured suspended load to get the observed total load. Table 2 shows the equations used for obtaining bed load for Shetrunji River.

Lane and Borland[36] discuss many factors to be considered in estimating the rate of bed load movement and conclude that it is not possible to develop a simple rule or formula that will give quantitative values for all streams. These conclusions have been summarized in Table 3 (ref. 37). Yang[38] found that bed load transport of a river is about 5–25% of that in suspension. Waikhom and Yadav[39] found this value to lie between 5% and 15%.

In the second approach, observed bed load data for Shetrunji River were generated using Maddock range (Table 3) and total load transport was determined by adding the generated bed load to the measured suspended load. Thus, the reliability of the above five selected bed load equations was tested by comparing the total load values computed with those of total load obtained using Maddock's range. Applicability of the selected Yang USP equations[24,25] for Shetrunji River was then determined by

Table 2. Selected bed load equations used

Approach to compute bed load	Year	Formula
Shields[2]	1936	$q_b\left[\frac{(\gamma_s-\gamma)/\gamma}{qS}\right]=10(\tau_0-\tau_c)/(\gamma_s-\gamma)d_S$
Swamee and Ohja[6]	1991	$\phi_b=\frac{q_b}{d_*((s-1)gd_*)^{1/2}}$
Parker[5]	1979	$\phi=11.20\left(\frac{(\theta-0.03)^{4.5}}{\theta^3}\right)$
Julien[7]	2002	$\phi=18\sqrt{g}d_s^{1.5}\theta^2/\sqrt{g(S-1)d_s^3}$
Recking[8]	2013	$\phi=q_{sv}/\sqrt{g(S-1)D_{84}^3}$ $\begin{cases}\phi=0.0005\left(\frac{d_{84}}{d_{50}}\right)^{-18\sqrt{S}}\left(\frac{\tau_{84}^*}{\tau_{c84}^*}\right)^{6.5} & \text{if } \tau_{84}^*<\tau_m^* \\ =14\tau_{84}^{*\frac{5}{2}} & \text{if } \tau_{84}^*<\tau_m^*\end{cases}$

ϕ_b is the bed load transport rate parameter, d_* the dimensionless sediment diameter, s the specific gravity, q_b the volumetric bed load transport rate per unit width of stream, q the water discharge, γ_s and γ are the unit weight of sediment particles and flowing fluid respectively. θ the dimensionless shear stress (Shield's parameter), ϕ dimensionless bedload transport parameter, q_{sv} the volumetric transport rate per unit width (m^3/s/m) and S is the specific gravity.

Table 3. Maddock's classification for determining bed load

Concentration of suspended load (ppm)	Type of bed material forming the stream channel	Texture of suspended material	Unmeasured bed load as a percentage of suspended load
<1000	Sand	Similar to bed material	25–150
<1000	Gravel, rock or consolidated clay	Small amounts of Sand	5–12
1000–7500	Sand	Similar to bed material	10–35
1000–7500	Gravel, rock or consolidated clay	25% of sand or less	5–12
>7500	Sand	Similar to bed material	5–15
>7500	Gravel, rock or consolidated clay	25% of sand or less	2–8

Table 4. Summary of obtained average bed load range using selected bed load equations

Bed load formula	Range of bed load data in concentration (ppm)
Shields[2]	0.0000003–0.0021
Swamee and Ohja[6]	0.00168–754.55
Parker[5]	0.26–5106.5
Julien[7]	2548.1–16,733,909.8
Recking[8]	0.597–269.08

Table 5. Summary of obtained average bed load range using Maddock's classification

Percentage of suspended load	Average range of bed load in concentration (ppm)
5	0.25–118.75
10	0.5–237.5
12	0.6–285

comparing the computed and predicted values of the total load transport rate.

Results and analysis

The results obtained using Yang USP equations[24,25] were analysed for understanding the degree of precision in predicting total load. Based on the observed suspended load concentration and texture of bed material (rock type) forming the channel of Shetrunji River (5.0–2375 ppm), bed load was computed using 5–12% of suspended load. Tables 4 and 5 provide a summary of the range obtained using the selected bed load equations and Maddock's range respectively.

These bed load results indicate that Julien[7] computed bed load largely outside the range obtained using Maddock classification. For selection of most accurate bed load equation, total load transport rate was obtained considering the five bed load equations selected. Further, the obtained total load was compared with that predicted using Yang USP total load equations. Deviation of the computed values from the observed values was found by calculating percentage error. Tables 6–9 give a comparative summary of the obtained total load (computed) and

Table 6. Comparison between average computed and average total load transport predicted using Yang[24] approach for Shetrunji River data

Approach used to compute bed load	Computed bed load (used as observed bed load in ppm) (A)	Observed suspended load (ppm) (B)	Observed total load (ppm) ($A + B$)	Predicted total load (ppm)	MPE (%)
Shields[2]	0.000016	210.945	210.95475	73.93	–43.30
Swamee and Ohja[6]	40.044	210.945	252.9989	73.93	–50.86
Parker[5]	258.483	210.945	469.43840	73.93	–79.63
Julien[7]	854855.5958	210.945	855066.55	73.93	–99.98
Recking[8]	16.50621	210.945	227.4609	73.93	–59.32

Table 7. Comparison between average obtained total transport load (according to Maddock range) and average predicted values using Yang[24] approach

Percentage of suspended load used as bed load	Computed bed load (used as observed bed load in ppm) (A)	Observed suspended load (ppm) (B)	Observed total load (ppm) ($A + B$)	Predicted total load (ppm)	MPE (%)
5	10.54	210.95	221.50	73.93	–45.80
10	29.09	210.95	232.05	73.93	–68.13
12	25.31	210.95	236.269	73.93	–68.70

Table 8. Comparison between average observed and average total load transport predicted using Yang[25] approach for Shetrunji River data

Approach used to compute bed load	Computed bed load (used as observed bed load in ppm) (A)	Observed suspended load (ppm) (B)	Observed total load (ppm) ($A + B$)	Predicted total load (ppm)	MPE (%)
Shields[2]	0.000017	210.945	217.956	29.24	–81.26
Parker[5]	259.02	210.945	476.98	29.24	–93.680
Swamee and Ohja[6]	41.81	210.945	259.771	29.24	–83.336
Julien[7]	860,204	210.945	860,422.008	29.24	–99.990
Recking[8]	16.519	210.945	234.475	29.24	–87.540

Table 9. Comparison between observed total transport load (according to Maddock range) and predicted values using Yang[25] approach

Percentage of suspended load used as bed load	Computed bed load (used as observed bed load in ppm) (A)	Observed suspended load (ppm) (B)	Observed total load (ppm) ($A + B$)	Predicted total load (ppm)	MPE (%)
5	10.54	210.945	221.485	29.24	–81.89
10	29.09	210.945	240.035	29.24	–82.72
12	25.31	210.945	236.255	29.24	–83.02

predicted total load using Yang USP equations[24,25] and the deviation of predicted values from observed values in terms of mean percentage error (MPE) respectively.

The best prediction of total load using Yang USP equation[24] was found when Shields' formula was used to compute bed load with MPE of –43.3%. This result is quite similar to the value (–45.8%) when total load is predicted using 5% of suspended load as bed load (Tables 6 and 7). Yang USP equation[24] also provided good prediction for Shetrunji River when bed load was computed using Swamee and Ohja[6], and Recking[8] bed load equations. It was also observed that the percentage error between predicted and computed (observed) values increased as the percentage of suspended load considered as unmeasured bed load increased from 5% to 10%; little variation in results was observed on further increasing this to 12%. It can be inferred that 5% of suspended load can be considered to be the computed bed load of Shetrunji River.

Analysis of the results indicates that the predicted value deviates from the observed value with an average error range of –81.26% to 93.68% (Tables 8 and 9). The error range was more compared to the values predicted using Yang USP equation[24] for the same bed load equations and range of suspended load. Though the error range is high, it was interesting to observe that the results obtained using Shields' formula for computing bed load were similar to those obtained when total load was

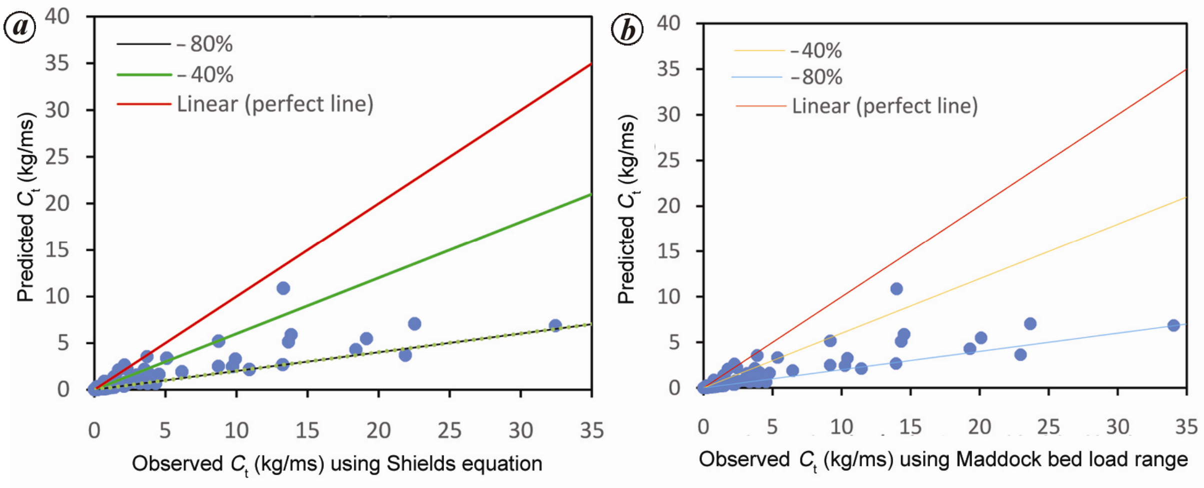

Figure 2. Percentage error between observed and predicted total load transport using (*a*) Shields' equations and (*b*) Maddock's range as bed load for Yang approach[24].

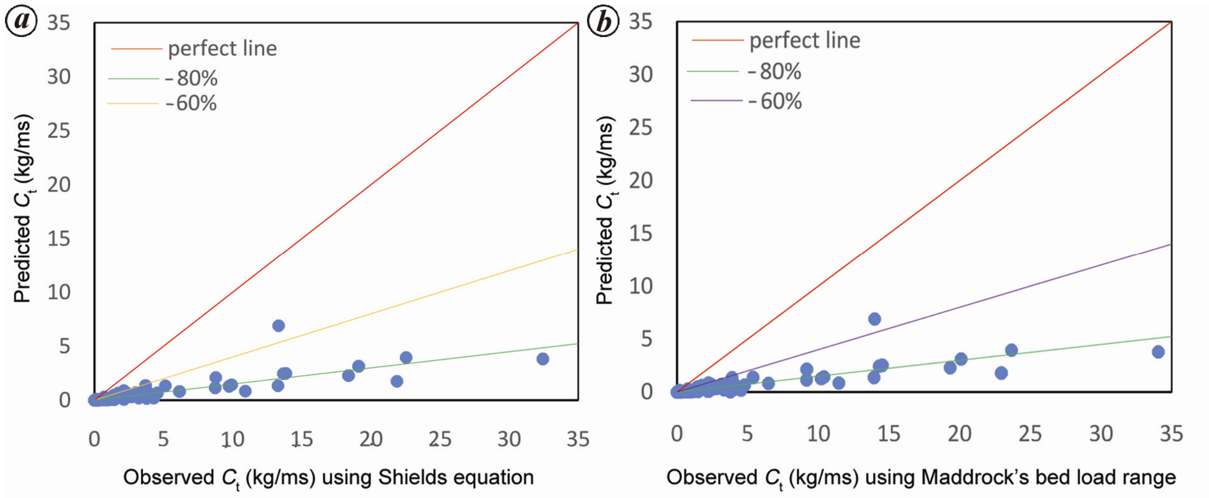

Figure 3. Percentage error between observed and predicted total load transport using (*a*) Shields' equations and (*b*) Maddock range as bed load for Yang[25] approach.

predicted using 5% of suspended load as bed load. It was found that the total load transport predicted using Yang USP equations[24,25] considering 5% of suspended load as unmeasured bed load gave near equal values of the results obtained using Shields' bed load formula. Further analysis was done taking (i) 5% of suspended load as unmeasured bed load and (ii) bed load obtained using Shields' bed load equation.

To check the applicability and performance of Yang USP equations for Shetrunji River data, various statistical measures were calculated. The discrepancy ratio (DR) is the ratio of calculated and measured values of total load. DR calculated for each data point was considered for comparison of performance. If DR <1, the equation under predicts the measured data and vice versa.

Deviation of predicted value from observed value using Yang USP equations[24,25] was plotted by calculating percentage error (Figures 2 and 3). The solid line in Figures 2 and 3 represents the line of equal or perfect agreement. The percentage of data coverage between accepted lower and upper limits of DR (score in terms of percentage of DR within the range 0.5–2.0) was calculated and statistical properties such as root mean square error (RMSE) and inequality coefficient (U) were taken as the criteria of goodness of fit. The RMSE is one of the most convenient and precise statistical parameters for assessing simulation models. It measures the deviation between the trend of the predicted and measured values. The zero value of RMSE indicates a perfect fit between measured and predicted values. Inequality coefficient is a simulation statistics related to RMSE. If $U = 0$, then predicted values are equal to observed values and there is a perfect fit.

It can be observed from Figure 2 *a* and *b* that maximum proportion of the predicted total load transport rate is

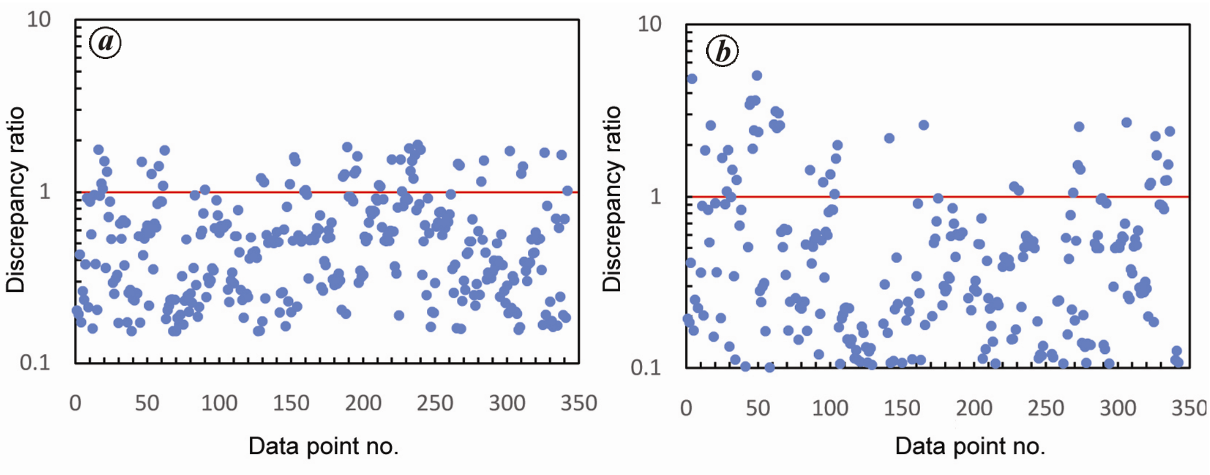

Figure 4. Verification of Yang[24] Unit Stream Power for Shetrunji River data using (***a***) Shields' bed load formula and (***b***) Maddock's bed load range.

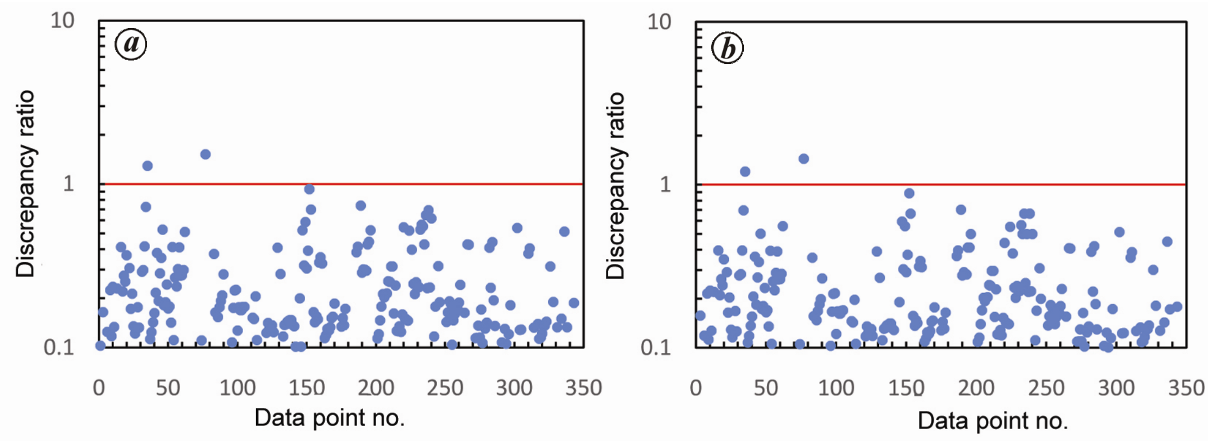

Figure 5. Verification of Yang[25] Unit Stream Power for Shetrunji River data using (***a***) Shields' bed load formula and (***b***) Maddock's bed load range.

Table 10. Summary of statistical parameters using the methods of Shields and Maddock as observed bed load data

	Root Mean Square Error		DR		Inequality coefficient		MPE (%)	
Approach	Maddock	Shields	Maddock	Shields	Maddock	Shields	Maddock	Shields
Yang[24]	3.29	3.7234	0.5461	0.5703	0.6987	0.6873	–45.80	–43.30
Yang[25]	4.23	4.016	0.1788	0.1883	0.8262	0.8187	–82.190	–81.26

below the line of equality. So the Yang USP equation[24] underpredicts for Shetrunji River data. Few data points are found to be overpredicted. The percentage error between the observed and predicted transport rates lies mostly in the range of –40 to 80. A similar trend of prediction and deviation of predicted value from the observed value was observed when total load was obtained using Shields' formula or Maddock range. From Figure 3 *a* and *b*, it is seen that maximum of the predicted total load transport rate is below the line of equality. So Yang USP equation[24] underpredicts for Shetrunji River data. Few data points are found to be near the line of equality. The percentage error between the computed and predicted transport rate is in the range 10 to –90, but most of data lie between –60 and –80. A similar trend of prediction and deviation of predicted value from the observed value was observed when total load was obtained using Shields' formula or Maddock range. Thus it can be inferred that Shields' formula provides consistent results with the Maddock range for Yang equations[24,25]. Thus unmeasured bed load of Shetrunji River may be obtained using Shields' bed load formula. Figures 4 and 5

Table 11. Comparison of accuracy of unit stream power equations for Shetrunji River data

Type of total load	Yang equation[24]	Yang equation[25]
	Score (discrepancy ratio within the range 0.5–2.0)	
Total load (using Shields bed load)	51.1695	3.684
Total load (using Maddock range)	41.5204	10.70
Ranking	1	2

show a graphical representation of DR for both the approaches.

It can be observed that the range of DR computed using Maddock's and Shields' approach yields similar results for Yang USP equations[24,25] (Figures 4 and 5).

Table 10 provides a comparative summary of statistical parameters used to evaluate the performance of Yang USP equations[24,25].

For comparing the accuracy of USP equations for Shetrunji River data, the percentage of data within DR 0.5–2.0 as score is shown in Table 11; the equation having the highest score is ranked first.

Conclusion

In the absence of measured data, bed load has been calculated using five different relationships. Bed load has also been calculated using Maddock's approach based on sediment concentration and mean sediment size.

The calculated total load (using bed load equations) was compared with predicted total load (for both the Yang approaches[24,25]). Based on MPE in this comparison, Shields' bed load equation was most suitable among the five bed load equations.

The calculated total load (using Maddock's bed load estimation) was compared with predicted total load for both Yang approaches. The minimum MPE was obtained when 5% of suspended load was taken as bed load in both approaches.

Total sediment load was computed using two approaches independently. First, the total sediment load was calculated by adding bed load (computed using different bed load equations) and observed suspended load (obtained from CWC). Secondly, the total sediment load was calculated by adding bed load (computed using Maddock's approach) and observed suspended load.

Total load prediction by USP equations was assessed using statistical measures. The comparison was done taking into consideration both values of computed bed load. Statistical parameters of performance like RMSE, DR, *U* and score for the Shetrunji River data were evaluated for analysis of results of these two approaches.

The score for Yang USP equation[24] was far better than that for Yang USP equation[25].

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Received 12 July 2016; revised accepted 22 March 2017

doi: 10.18520/cs/v113/i06/1120-1128