

A Critical Study Of Total Bed Material Load Predictors

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Abstract- *The accurate estimation of sediment transport rate in alluvial channels is vital for safe and economical design of canals and other hydraulic structures. The total bed material load transport phenomenon depends on such a large variety of circumstances that it is difficult to define such definite laws that would suggest prediction of total bed material load transport rate at a particular location in a stream with 100% accuracy. Moreover, despite vast knowledge gained from the intensive research carried out on this phenomenon, no definite solution is yet available. There are several total bed material transport predictors available; however, these predictors produce wide range of total bed material load estimates transport rate for the same set of data. In this paper an effort has been made to ascertain which of the predictors produce a reasonable estimate of the total bed material load transport rate that can be used by field engineers and researchers in the designs of hydraulic structures. Ten well known total bed material load predictors are testified against the reliable published field data. A new model for predicting total bed material load is also developed using the same set of data. The study reveals that authors predictor followed by Ackers and White, Karim & Kennedy and Engelund & Hansen predictors produce more reasonable estimate of total bed material transport rate.*

Key Words: *Sediment, transport, bed load, total load, prediction.*

1. INTRODUCTION

Total bed material load is a measure of rate of transport of sediments in alluvial channels. The knowledge of rate of total sediment transport for given flow, fluid and sediment characteristics are essential in the study of field alluvial problems, i.e., the design of hydraulic structures and alluvial channel.

In addition to this problems such as aggradations and degradation, river training, reservoir sedimentation, etc. also depend on the knowledge of total bed material load

transport. The phenomena of sediments transport is governed by several interrelated parameters.

Ab. Ghani (1993) describes the fundamental parameters that govern the sediment transport processes in steady or gradually varied free surface flow in alluvial channels namely flow depth (y_0), hydraulic radius (R), mean flow velocity (v), shear stress (τ_0), kinematic viscosity (ν), density of water (ρ), sediment size (d), particle density (ρ_s), volumetric concentration of sediment (C_v), cross-section geometry (B and y_0), bed roughness (n), friction factor (f), bed slope (S_0) and acceleration due to gravity (g). Shields proposed two non-dimensional numbers: Shear Reynolds number (R_{*c}) and Non-dimensional shear stress (τ_{*c}) which govern the sediment transport processes. The parameters like Shear Reynolds number (R_{*c}), Non-dimensional shear stress (τ_{*c}), total load function (Φ_T) and particle fall velocity (ω_s) proposed by different investigators also govern the sediment transport processes significantly.

A number of total bed load material transport rate predictors have been developed by several investigators (Ab. Ghani 1993; Karim 1998; Molinas and Wu 2001, Laursen (1958), Garde et al. (1963), Graf (1968), Engelund and Hansen (1967), Ackers and White (1973), Yalin (1977), Brownlie (1981), Yang (1973, 1984, 1996), Karim and Kennedy (1983), Raudkivi (1990), Ariffin (2004) and Sinnakaudan et al. (2006)). These predictors were developed using limited set of laboratory data and field data obtained from different sources.

Despite vast knowledge gained from the intensive research carried out on the sediment transport phenomenon, none of the published sediment transport predictors have gained universal acceptance in confidently predicting sediment transport rates, especially in rivers (Yang, 1996). Different characteristic parameters have been proposed previously to calculate the sediment concentration. Yang (1996) developed a formula to estimate total bed material load in a sediment laden river with high concentration of fine material. He derived his sediment concentration functions using multiple linear regression analysis of

laboratory data, based on his unit stream power theory. Molinas and Wu in 2001 had proposed the use of energy concept in the development of sediment transport equation based on universal stream power by Yang (1996).

These predictors produce wide range of total bed material load estimates for the same set of data which is a problem for hydraulic engineers that which of the predictors should be used to estimate the total bed material load transport rate that can be used by field engineers and researchers in the designs of hydraulic structures with confidence. In this paper the ten commonly used and cited total bed material load transport rate predictors namely Garde and Dattari (1963), Engelund and Hansen (1967), Graf and Acaroglu (1968), Ackers and White (1972), Yang (1973), Brownlie (1981), Karim and Kennedy (1983), Yang (1996), Ariffin (2004) and Sinnakaudan (2006) are examined against the reliable published field data obtained from various sources in order to find the more accurate total bed material load predictor and a general equation is developed for total bed material load prediction. Using same set of data that has been used in this study, a new predictor has also been proposed for estimating the total bed material load rate.

2. COLLECTION OF DATA USED IN PRESENT STUDY

The wide range of data of various flow and sediment variables which has been used in present study are given in Table 1.

Table 1: Range of Hydraulic and sediment data used in present study

Parameters	Mini.mu	Max.
Discharge, Q (m ³ /s)	0.00094	28825.
Flow velocity, V (m/s)	0.14389	3.3222
Channel bed width, B (m)	0.346	1109.4
Flow depth, y (m)	0.0189	16.428
Bed Slope, S ₀	0.00001	0.0126
D50 (mm)	0.021	50.916
Sediment conc, C (ppm)	4.016	11400

As given in Table 1, in present study, a total number of 137 sets of hydraulic and sediment data covering wide range of flow and sediment conditions have been taken from the Compendium of Alluvial Channel data compiled and published by W.R. Brownlie. The ranges of physical parameters of field data used in this study are shown in Table 1.

3. SELECTION OF PARAMETERS AND DEVELOPMENT OF NEW TOTAL BED MATERIAL LOAD PREDICTOR

Various factors affect the phenomena of total bed material load transport. Ab. Ghani (1993) describes the fundamental parameters that govern the sediment transport processes in steady or gradually varied free surface flow in open channels consisting of the flow depth (y₀), hydraulic radius (R), mean flow velocity (v), shear stress (τ₀), kinematic viscosity (ν), density of water (ρ), sediment size (d), particle density (ρ_s), volumetric concentration of sediment (C_v), cross-section geometry (B and y₀), bed roughness (n), friction factor (f), bed slope (S₀) and acceleration due to gravity (g). Shields proposed two non-dimensional numbers: Shear Reynolds number (R_{*c}) and Non-dimensional shear stress (τ_{*c}) which govern the sediment transport processes. The parameters like Shear Reynolds number (R_{*c}), Non-dimensional shear stress (τ_{*c}), total load function (Φ_T) and particle fall velocity (ω_s) proposed by different investigators also govern the sediment transport processes significantly.

For developing new total bed material load predictor, the most significant parameters have been selected by carrying out factor analysis on the various available parameters which may govern of total bed material load concentration. Factor analysis is concerned with interpreting the structure of the variance and covariance matrix obtained from a collection of multivariate observations. Factor analysis is performed to find out the most significant independent variables affecting the dependent variable. Based on factor analysis performed on various parameters influencing the total bed material transport rate following parameters are found to be more significant:

- (i) Total load parameter (Φ_T)
- (ii) Dimensionless shear stress (τ_{*})
- (iii) Darcy-Weisbach friction factor (f)

After finding most significant parameters affecting the phenomena of sediment transport, regression analysis was performed on the selected parameters to develop new total bed material load predictor as under with correlation coefficient [R²=0.7382]: $f \Phi_T = 0.3917 \cdot \tau_*^{2.4417}$ (1)

where

$$\text{Total load function, } \Phi_T = \frac{q_T}{\gamma_s (g d^3)^{1/2}} \cdot \frac{1}{\left(\frac{\tau_*}{\gamma_f}\right)^{1/2}}$$

$$\text{Non dimensional shear, } \tau_* = \frac{\tau_0}{[\gamma_s - \gamma_f] d}$$

$$\text{Darcy-Weisbach friction factor, } f = \frac{8 g n^2 g}{v^2}$$

4. VERIFICATION OF TOTAL BED MATERIAL LOAD PREDICTORS USED IN PRESENT STUDY WITH OBSERVED DATA:

Applying the selected total bed material load predictors to the selected data, the values of total bed material load were computed and were compared with the observed values of total bed material load in order to assess the accuracy of selected ten total bed material load predictors. Thereafter, analysis of the results was made in three ways: (1) In first approach, the accuracy of each predictor was assessed by comparing the measured and computed values of total bed material load between a discrepancy ratio range of 0.5 to 2.0. The discrepancy ratio can be defined as the ratio of computed and measured values of total bed material load. Percentile scores of all the ten predictors considered in this study and authors' newly developed predictor in the discrepancy ratio range of 0.5 to 2.0 were computed [Table 2] to assess the accuracy of each predictor.

(2) In second approach, the computed values obtained from each total bed material load predictor selected in present study were plotted against the observed values of total bed material load [Fig. 1 to.11]. The scattering of data points around line of goodness indicates the accuracy of the corresponding predictor. The closeness of the plotted data points to the goodness line indicates good performance of the predictor.

(3) In third approach, the values of statistical parameters, like mean standard error, correlation coefficient and average geometric deviation were computed [Table 3] to assess the accuracy of each predictor.

Table 2: Percentage of data falling within

Predictor	Percentile scores within discrepancy ratio range (0.5-2.0)
Garde and Dattari's Formula (1963)	25.0
Engelund and Hansen's Formula (1967)	48.38
Graf and Acaroglu's Formula	34.67
Yang's Formula (1973)	36.29
Ackers and White's Formula (1973)	50.0
Brownlie's Formula (1981)	45.96

* Mean Standard Error is used in order to select the best total bed material load predictor due to large difference between observed and calculated total sediment load. The value of MNE closer to zero shows higher accuracy of predictor.

$$\text{Mean Standard Error (MNE)} = \frac{100}{N} \sum_{i=1}^N \left| \frac{C_{obs} - C_{cal}}{C_{cal}} \right|$$

N = number of data

C_{obs} = Observed sediment load

total sediment load

C_{cal} = Calculated total

* Average geometric deviation measures the geometric mean of the discrepancy between observed and calculated total sediment load. The value of Average geometric deviation closer to unity shows higher accuracy of predictor.

$$\text{Average Geometric Deviation (AGD)} = \left(\prod_{i=1}^N R_i \right)^{1/N}$$

$$\begin{cases} C_{cal}/C_{obs} & \text{if } C_{cal} \geq C_{obs} \\ C_{obs}/C_{cal} & \text{if } C_{cal} < C_{obs} \end{cases}$$

*The correlation coefficient between observed and predicted values varies from 0 to 1. A small value indicates little or no linear relationship between dependent variable and independent variables.

$$\text{Correlation coefficient} = \frac{SS_R}{SS_T}$$

The analysis has been performed on the selected data neglecting the data producing infinite or Indeterminate values of MNE and AGD. e Tabl3. Statistical analysis of ten selected predictors and authors' predictor.

Karim and Kennedy's Formula (1983)		48.38	
Yang's Formula (1996)		25.0	
Ariffin's Formula (2004)		22.58	
Sinnakaudan et al. Formula (2006)		16.93	
Present study		47.58	
Predictor used	Mean Standard Error (MNE)	Average Geometric Deviation (AGD)	Correlation Coefficient
Garde-Dattari's	830.72	7.23	0.2579
Engelund-Hansen's	95.31	2.59	0.528

Graf-Acaroglu's	150.77	3.65	0.4014
Yang's Formula	321.83	4.15	0.3727
Ackers-White's	248.47	2.77	0.6452
Brownlie's Formula	182.36	2.83	0.7008
Karim-Kennedy's	188.23	2.94	0.4291
Yang's Formula	590.45	5.15	0.398
Ariffin's Formula	680.13	5.02	0.4841
Sinnakaudan et al.	1028.68	5.83	0.4545
Present	97.04	2.59	0.5523

RESULTS AND ANALYSIS

The values of total bed material load concentration obtained from the total bed material load predictors considered in this study using the published field data are compared. The accuracy of the selected predictors is assessed by three approaches, firstly by comparing the results obtained from each predictor in the discrepancy ratio range of 0.5 to 2.0, secondly by plotting scatter graphs between measured and predicted values of total bed material load and thirdly by statistical check.

A new empirical relationship is also developed in present study using the same data that are used for the evaluation of different predictors in this study.

In first approach the percentages of results falling within discrepancy ratio range of 0.5 to 2.0 are plotted and shown in Table 1. It can be observed from Table 1 that authors' predictor followed predictors of Ackers and White, Karim and Kennedy, Engelund and Hansen, Brownlie, Yang (1973, 1996) produce more accurate result as compared to other predictors used in present study

In second approach the scatter graphs are drawn between measured and predicted values of total bed material load obtained from authors' predictor and ten total bed

CONCLUSIONS

Ten well-known predictors of Engelund and Hansen, Ackers and White, Karim and Kennedy, Garde and Dattari, Graf and Acaroglu, Yang, Brownlie, Ariffin and Sinnakaudan are used to examine their predicting ability of total bed material load using published field data covering a wide range of flow and sediment conditions.

material load predictors used in this study as shown in figures 1-12. These figures depict that the scattering of data points around the goodness line is less in authors' predictors and the predictors of Ackers and White, Karim and Kennedy, Engelund and Hansen, Brownlie, Yang (1973, 1996); which implies that these predictors yield more reasonable results. The scatter graphs shown in figures (1, 3, 9 & 10) depict large scattering around the goodness line; which indicates that predictors of Garde and Dattari, Graf and Acaroglu, Ariffin and Sinnakaudan produce less accurate results.

Similarity in the scatter trend in all the predictors except Sinnakaudan and Ariffin, can be observed in the scatter graphs shown in Fig. 9 and Fig. 10. The reason of the variation in the scatter trend of Sinnakaudan and Ariffin predictors can be attributed to the data used in present study and data used (Malaysian river data) by these authors in the development of their predictors. Sinnakaudan and Ariffin have used Malaysian river data in the development of their predictors. It is suggested that the study can be extended by using Malaysian river data also. The measured and computed values of total bed material load obtained from all predictors used in this study and authors' predictor are plotted together as shown in Fig. 12. The two lines shown in Fig. 12 indicate the band of discrepancy ratio range of 0.5 to 2.0. Most of the results obtained from predictors of Ackers and White, Karim and Kennedy, Engelund and Hansen, Brownlie, Yang (1973, 1996) and present study lie within the discrepancy ratio range of 0.5 to 2.0.

In third approach the values of statistical parameters, like mean standard error, correlation coefficient 'R' and average geometric deviation are computed to assess the accuracy of each predictor are shown in Table 3 for field data. It can be concluded from Table 3 that authors' predictor and the predictors of Engelund and Hansen, Graf, Karim and Kennedy, Yang, Brownlie produce lower value of mean standard error, average geometric deviation; and higher value of correlation coefficient than the corresponding values of other predictors.

A new relationship is also developed using the same set of data that are used for the evaluation of ten predictors in this study.

The accuracy of each predictor is assessed by comparing the measured values and computed values of total bed material load between discrepancy ratio range of 0.5 to 2.0, by plotting the scatter graphs between measured and computed values of total bed material load and by statistical parameters; mean standard error, average

geometric deviation and correlation coefficient produced by each predictor.

The reason of the variation in the scattering trend in scatter graphs [Fig. 9 and Fig. 10] of Sinnakaudan and Ariffin predictors can be attributed to the data used in present study and data used (Malaysian river data) by these authors in the development of their predictors. It is suggested that Malaysian river data can also be used in further study.

LIST OF NOTATIONS

B	Bed width of channel
\bar{C}	Sediment concentration by weight
C_v	Volumetric concentration
\bar{C}_T, \bar{C}	Total load concentration in ppm by weight
D, y_0	Depth of flow
d, d_{50}	Median size of sediment
d_*	Dimensionless particle diameter
f	Darcy-Weisbach friction factor
G, s, S_s	Specific gravity of sediment
g	Gravitational acceleration
n	Manning's roughness coefficient
Q	Total discharge
q_T, q_T	Total load transp./unit width of channel
R	Hydraulic radius
R_*	Shear Reynolds number
SS_R	Regression sum of squares
SS_T	Total sum of squares

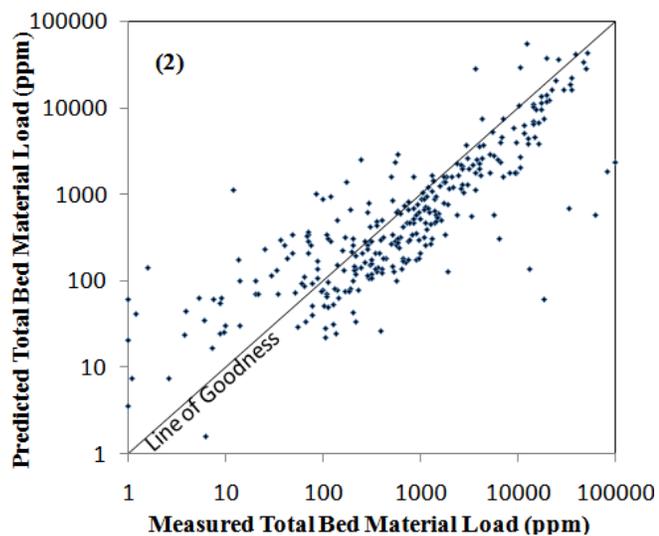
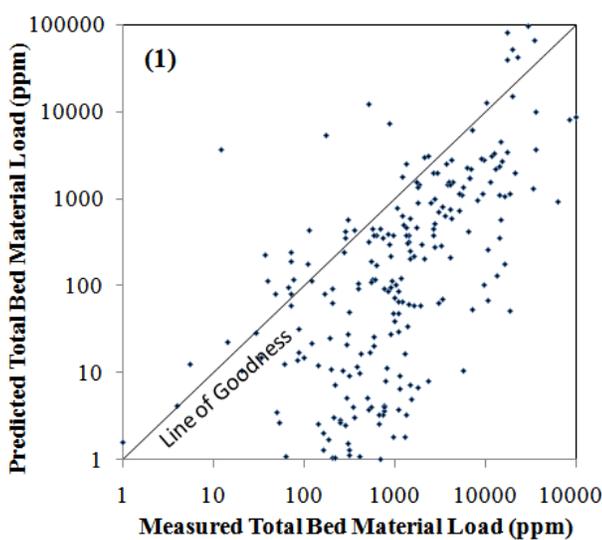
S_0	Bed slope
U_{cr}	Critical velocity of flow
u_*	Shear velocity
u_{*c}	Critical shear velocity
U, V	Mean velocity of flow
τ_0	Bed shear stress
τ_*	Dimensionless shear stress
τ_{*c}	Dimensionless critical shear stress
Φ_T	Total load function
γ_s	Unit weight of sediment
γ_f	Unit weight of fluid
ρ_f	Mass density of fluid
ρ_s	Mass density of sediment
ω_0	Fall velocity of sediment under ideal condition
ω_s	Fall velocity of sediment particle
ν	Kinematic viscosity of fluid
σ_a	Geometric standard deviation

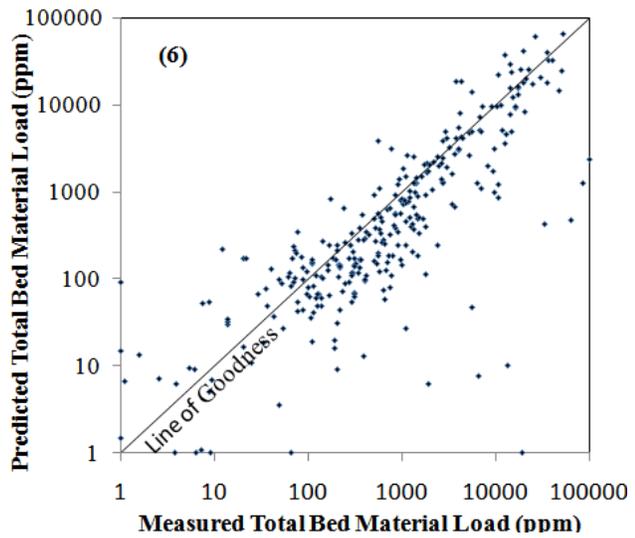
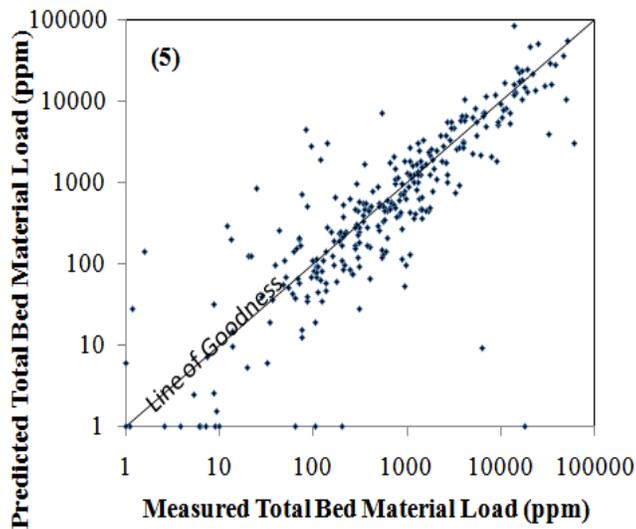
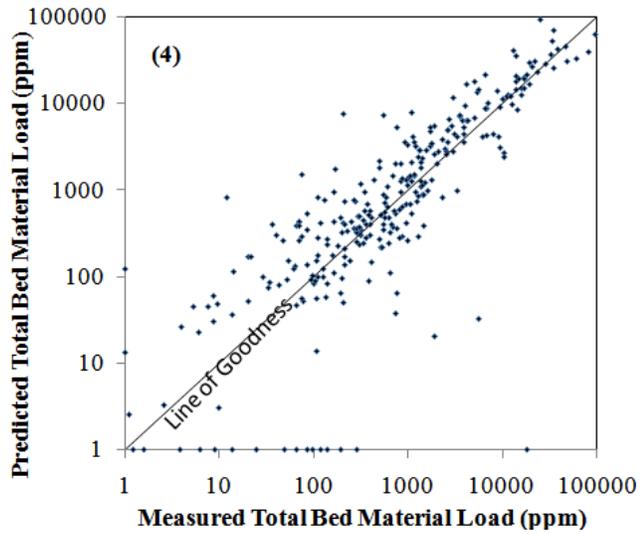
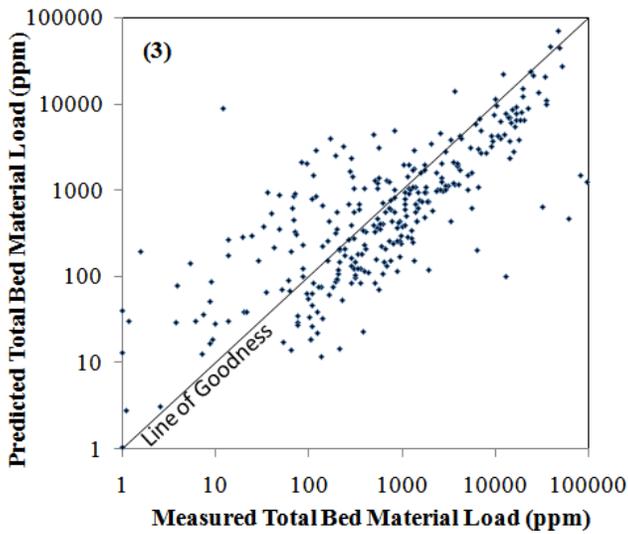
It can be concluded that **author's predictor and** the predictors of Ackers and White, Karim and Kennedy, Englund and Hansen, Brownlie produce more reasonable estimate of total bed material load and thus these predictors can be used by the field engineers with more confidence for the computation of total bed material load needed in the design of hydraulic structures.

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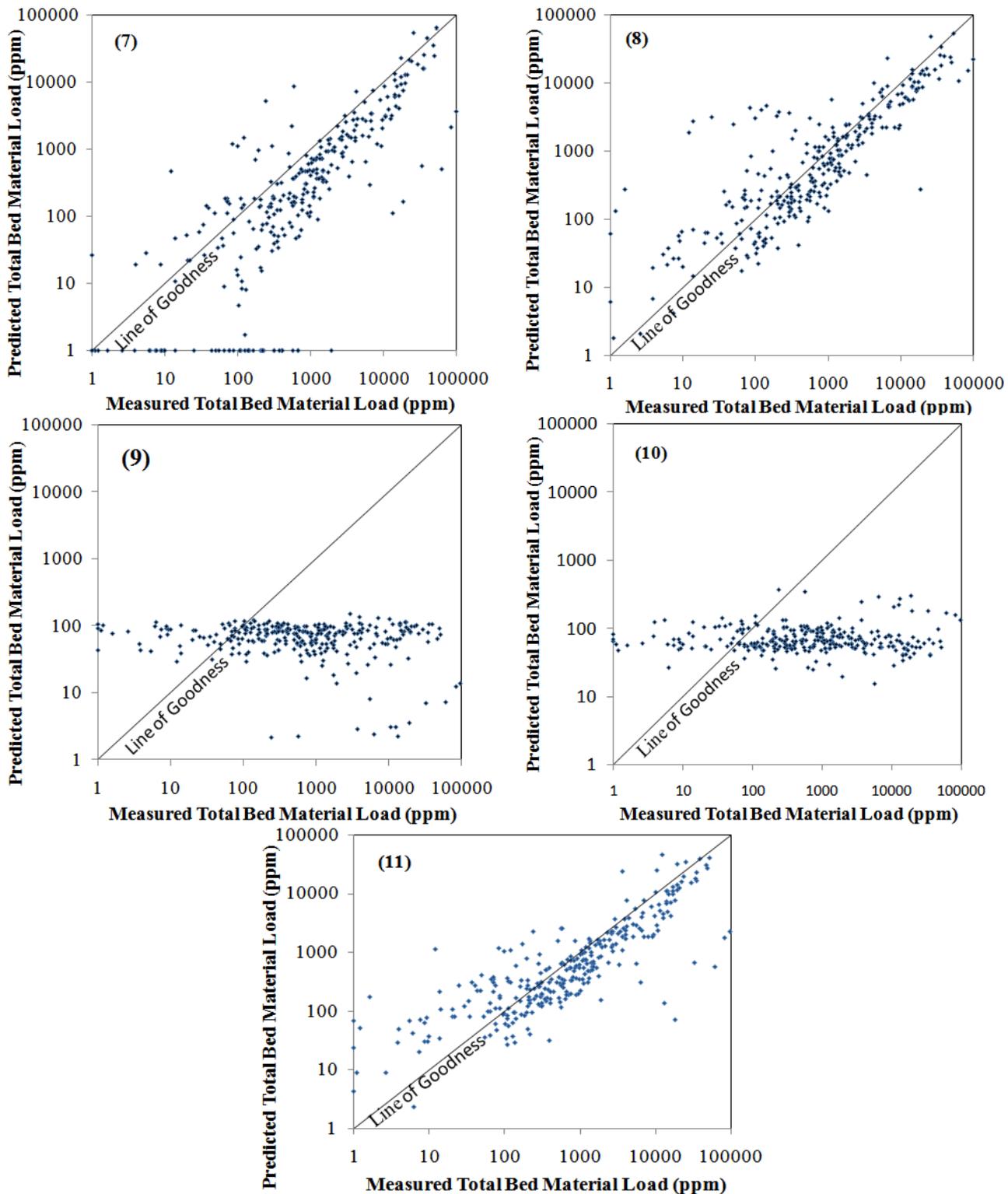


Fig. 1-11: Verification of the predictors of : (1) Garde-Dattari ;(2) Englund-Hansen (3); Graf-Acaroglu (4) ;Yang (1973); (5) Ackers-White; (6) Brownlie; (7); Karim-Kennedy Formula (8); Yang (1996); (9) Ariffin; (10) Sinnakaudan; (11) Present study

Appendix-2: Source of Data, Number Of Data And Data Range

Data Source (No. of data)	Q(m ³ /s)	V(m/s)	B(m)	y(m)	S ₀ (%)	d ₅₀ (mm)	C _v (ppm)
ACOP Canal(10)	29.59-486.82	0.49-1.27	35.66-128.32	1.68-2.19	0.0085-0.0146	0.085-0.21	34-2083
American River (3)	1.22-29.19	0.47-0.74	3.2-22.19	0.8-2.53	0.0058-0.0331	0.222-7	99.1-448
Atchafalaya river(5)	1393-14186	0.64-1.96	316.9-503.2	6.88-14.72	0.0011-0.0051	0.091-0.226	38.22-501.22
Chitale Canal(5)	3-242.19	0.472-0.949	5.78-79.09	1.1-3.56	0.0064-0.0114	0.021-0.064	981-5758.99
Chop Canal(10)	27.52-427.57	0.6906-1.5369	23.774-121.615	1.3106-3.4138	0.0085-0.0202	0.09-0.311	232.336-1316.88
Colorado River(8)	77.5315-500.1605	0.5307-0.8953	95.167-254.55	1.1339-3.3132	0.0133-0.0277	0.175-0.36	22.7-768.7
Hill River(8)	0.0009-4.8513	0.1439-0.9299	0.346-8.001	0.0189-0.652	0.084-0.839	0.21-1.44	116.553-5638.613
Middle Loup(6)	9.3726-12.4873	0.6216-0.876	44.806-46.33	0.2707-0.4118	0.125-0.133	0.344-0.395	482.24-2444
Mississippi River(7)	3567.815-28825.7	0.8376-1.5814	479.145-1109.472	6.5837-16.428	0.0031-0.0118	0.173-0.31	25.859-320.575
Mountain Creek(10)	0.0644-1.4631	0.3961-0.7802	3.551-4.334	0.0396-0.4327	0.137-0.315	0.286-0.899	72.65-2600.582
Rio Magdalena(8)	81.9998-10199.99	0.5256-1.3669	36-582	1.32-13.28	0.0024-0.046	0.1-1.08	99.473-2000.352
Niobrara River(6)	5.918-16.0552	0.6683-1.2707	21.031-21.946	0.421-0.5757	0.125-0.1799	0.218-0.329	392-2339.998
Saskatchewan River(7)	4.7096-33.1091	2.1123-3.3223	3.048-6.096	0.7315-2.1946	0.158-1.26	17.6-50.916	32.236-760.168
Red River(8)	190.2833-1537.56	0.4073-1.1398	140.513-182.88	2.9992-7.3762	0.0066-0.0077	0.108-0.204	26.494-499.751
Rio Grande River(25)	1.9198-285.9915	0.4265-2.3493	20.422-194.462	0.2408-3.112	0.053-0.235	0.18-0.645	129-114
Snake River(7)	971.2385-2888.23	1.6835-2.9971	137.16-198.12	4.2062-5.9131	0.0245-0.121	0.42- 25	4.016-32.687
Trinity River(4)	39.6424-82.6826	1.2658-2.1774	30.175-53.95	0.6614-1.1979	0.26-0.3	3.4 -11.8	36.269-674.84