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Uncertainties in Evaluation of the Sediment Transport Rates in Typical Coarse-Bed Rivers in Iran

Mehdi Yasi[1*], Rahim Hamzepouri[2], Alireza Yasi[3]

1. Department of Water Engineering, Urmia University, Iran
2. Office of River Engineering, West Azarbaijan Water Company, Iran
3. Department of Civil Engineering, UTM University, Malaysia

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ABSTRACT

Flow and sediment transport processes are different and more complex in coarse-bed rivers than in sand-bed rivers. The main goal of the present study is to evaluate different modes of sediment transport using different hydrometric and hydraulic methods, and to address the major uncertainties. Four river reaches were selected as representatives of coarse-bed rivers in the Northwest of Iran. A sediment transport model (STM) has been developed to calculate the sediment loads from 5 hydrometric and about 60 hydraulic methods. The extent of the data and flow domain and also the effects of bed material characteristics were examined. The order of prediction intervals of 50%, 75% and 90% were determined. Results indicated that the order of 40% to 70% error is expected despite using the standard sediment measuring system and fitting the measured data to the best predictors. Predictions from the best-fitted hydraulic relationships indicated an order of error between 77% and 200%. This paper presents the prediction results and the order of errors for different modes of sediment loads applicable to similar coarse-bed river reaches.

Keywords

Coarse-Bed rivers; Sediment transport; STM model; Uncertainties

1. Introduction

Coarse-bed Rivers are characterized by relatively high degrees of bed slope, stream power, sediment transport, particularly in the mode of bed load; and are relatively wide and shallow with potential of deposition of non-cohesive coarse sediment such as gravel and cobbles (Przedwojski, et al. 1995). The process of flow and sediment transport is different and more complex in coarse-bed rivers than in sand-bed rivers. The main characteristic of the flow in coarse-bed rivers is the development of an armor layer with coarse gravel, cobbles and boulders. While this surface layer establishes a stable and smooth boundary at low to mean flows, its mobility introduces a different mode of the flow resistance during high flows resulting in excessive bed load transport of finer sub-surface material, and channel instability (Hey, et al. 1982; Parker, et al. 1982). Reliable prediction of the sediment transport capacity and determination of the different modes of transport (i.e. bed load, suspended load, and total load) in coarse-bed rivers are of major importance in river engineering.

* Corresponding Author Email: (m_yasi@yahoo.com)

Field data on suspended loads are more readily available, although less data are taken during high flows. Direct measurements of bed load are difficult to achieve, and less data is available (Boiten 2000; Kleinhans and Brinke 2001; Wilcock and Corwe 2003). Therefore, the evaluation of total sediment load, and the contribution of bed load to the total load are uncertain. The conventional approach suggests a small portion of suspended load is to be taken into account for the bed load (usually 5 to 25 percent). Such a fraction is generally applied to sand-bed rivers, but might be greater than 25% in coarse-bed rivers (Yang 1996). Linsely and Franzini (1979) suggested that this ratio is to be generally between 10% to 50%, but a greater percent is expected when considering the ratio of bed load to total load, and even much greater in the case of coarse-bed rivers. The ratio of bed to total load was found to be in the range of 0.4 to 0.8 with an average value of 0.57 (Yasi and Hamzepouri 2008). However, the order of 40% to 50% error is expected, even in standard sediment measuring system and in high flows.

Several relationships are available in the literature for predicting sediment transport in rivers. Some of these evaluate the total load directly (e.g. Karim and Kennedy 1990), a few methods calculate both the suspended and bed loads on an identical basis (e.g. Einstein 1950), and others compute either suspended load (e.g. Englund 1966) or bed load (e.g. Parker 1990). There is no general guidance to selection of the best methods applicable to different rivers, or different reaches of a river. The best selection among different relationships is unreliable wherever the field investigations are not involved in the river reach. The effects of bed sediment characteristics are to be considered in the adoption of the available relationships (Almedeij and Diplas2003; Habersack and Laronne 2002).

Hydraulic methods intend to calculate the capacity of sediment transport in a river reach under two conditions: (1) steady flow over a sufficient time span; and (2) non-uniform with gradually varied flow over sufficient length of the river (Yang 1996 and 2006). Sediment transport capacity of a river (often called as equilibrium sediment transport) is defined as the quantity of sediment that can be carried by the flow without net erosion or sedimentation. In unsteady and non-uniform flows, the actual sediment transport rate may be smaller or larger than the transport capacity resulting in net erosion or deposition, assuming sufficient availability of bed material (van Rijn 1993). There is no general relationship between the actual and the capacity of sediment transport. However, in the morpho-dynamic models, three conditions are considered in using the hydraulic sediment transport methods: (1) quasi-steady process by taking sufficient time step of Δt; (2) uniform flow over a limited river length of Δx; and (3) parameters accounting for time/space lag, L_s and α, known as non-equilibrium adaptation length and recovery factor for non-equilibrium sedimentation processes, respectively (Wu and Viera 2002; Abderrezzak and Paquier 2009). The quantitative values of L_s and α depend on the channel geometry, bed form, the size distribution of bed material and the intensity of bed/suspended loads; which are still difficult to determine (Han 1980; Yang, et al. 2006 and 2009). In coarse-bed rivers, the value of L_s was found to be small enough (a few meters), and of α could be negligible (van Rijn 1993; Abderrezzak and Paquier 2009). It is considered that the actual sediment transport rate can be taken equal to the transport capacity calculated by the hydraulic relationships in a sufficient length of coarse-bed rivers, but requires substantial adjustment in sand-bed rivers and for reservoir sedimentation process (Yang, et al. 2006; Yang and Marsooli 2010). However, the order of 50% to 70% error is expected, even when fitting the measured data to the best hydraulic predictors (van Rijn 1993). The main aim of the present study was to evaluate the different modes of sediment transports (i.e. bed, suspended and total loads) from different hydrometric and hydraulic methods in four representative coarse-bed river reaches, in Iran, and to address major uncertainties.

2. Materials and Methods

Three river reaches were selected as representatives of coarse-bed rivers in the North-West of Iran (Badalan reach in the Aland river; Yazdekan reach in the Ghotor river; and Baron reach in the Baron river). The extent of hydrometric data were also examined in another representative river reach in the region (Mashiran reach in the Dareroud river), where long-term and precise data are available. Presence of standard gauging station allowed for simultaneous measurements of bed and suspended loads in each of these four reaches. River survey and bed and sediment samplings were carried out in these river reaches (Hamzepouri 2005). Table 1 presents the characteristics of bed sediments from surface and subsurface layers, and from bed-load samplings in these reaches.

Mean flow characteristics were determined from the calibrated HEC-RAS model under different flow conditions in these river reaches, as presented in Table 2.

A sediment transport model (STM) was developed to accurately calculate the sediment loads from 5 hydrometric and about 60 hydraulic methods. Several relationships are adapted to coarse-bed rivers, most of which are presented in Table 3.

Figs. 1 to 3 show the evaluation of bed, suspended and total loads, respectively, in Badalan River reach using bed-load material characteristics. These figures indicate the prediction of bed loads from 13 relationships, of suspended loads from 4 relationships, and of total load from 10 relationships; also show the envelops and 90% confidence limits for the range of field data.

Table 1. Bed and sediment material characteristics in three river reaches

Reach (River)	Bed Material	D_{10} mm	D_{16} mm	D_{50} mm	D_{65} mm	D_{84} mm	D_{90} mm	C_u	σ_g	S_g
Badalan (Aland)	Surface	22.8	25.4	41	49.2	77.2	91	2.2	1.7	2.65
	Subsurface	0.42	.67	3.9	7.2	16.7	20.6	13.4	5.0	2.65
	Bed load	0.5	0.73	2.5	3.6	7.8	8.6	6	3.3	2.65
Yazdekan (Ghotor)	Surface	17	18.7	32.1	41.7	63.1	75	2.1	1.8	2.65
	Subsurface	0.6	0.9	3.7	6.8	14.5	22	9.2	4.0	2.65
	Bed load	0.7	0.95	3.7	6.4	13.7	20	8.5	4.8	2.65
Baron (Baron)	Surface	16	22	35	41	48.5	53	2.4	1.5	2.65
	Subsurface	0.4	0.57	3.6	8.8	24.5	29	16.1	6.5	2.65
	Bed load	0.47	0.6	1.9	2.8	4.8	7	5.3	2.8	2.65
Mashiran (Dareroud)	Subsurface	0.9	1.3	4.3	8.0	14.5	16.5	7.0	3.3	2.65

D_s = Characteristic size; C_u = Uniformity coefficient; σ_g = Geometric standard deviation; S_g = Specific gravity

Table 2. Flow characteristics in three river reaches

Reach (River)	Water flow rate Q (m^3/s)	Mean velocityV (m/s)	Water surface width B (m)	Hydraulic radius R (m)	Energy slope S (%)	Froude Number Fr (-)	Shear stress τ (N/m^2)
Badalan (Aland)	14.2	1.76	15.6	0.51	0.95	0.78	47.5
	36.6	2.43	17.8	0.83	0.93	0.84	76.2
	62.0	2.81	20.9	1.03	0.93	0.86	94.5
Yazdekan (Ghotor)	11.7	1.57	18.8	0.40	1.12	0.71	44.4
	48.7	2.46	22.9	0.85	0.95	0.75	79.3
	80.0	2.75	24.8	1.18	0.80	0.72	90.7
Baron (Baron)	50.0	1.44	84.1	0.42	0.81	0.64	33.7
	100.0	1.82	91.9	0.61	0.68	0.67	40.2
	166.0	2.19	101.	0.76	0.78	0.73	58.0
Mashiran (Dareroud)	13.2	1.1	30.7	0.42	0.55	0.50	20.4
	128.0	2.2	57.6	1.05	0.56	0.70	56.6
	206.0	2.5	71.1	1.21	0.50	0.70	58.0

Similar results could be demonstrated for the inclusion of either surface layer or sub-surface layer, and for the four river reaches.

In this study, the bed load was computed from 13 methods, the suspended load from 4 relationships, and the total load from 10 methods, using STM model. Sediment transport rates (i.e. suspended and bed loads, thereby the total load) were also evaluated from five different hydrometric methods, and compared with the corresponding results from hydraulic methods. The extent of hydrometric data and of flow domain, and the effects of bed material characteristics (surface layer, subsur-face layer, and bed-load material) were examined. Relative predictive errors are calculated from the difference between the estimated values divided by the observed data. The order of prediction intervals of 50%, 75% and 90% were determined for the sediment yield.

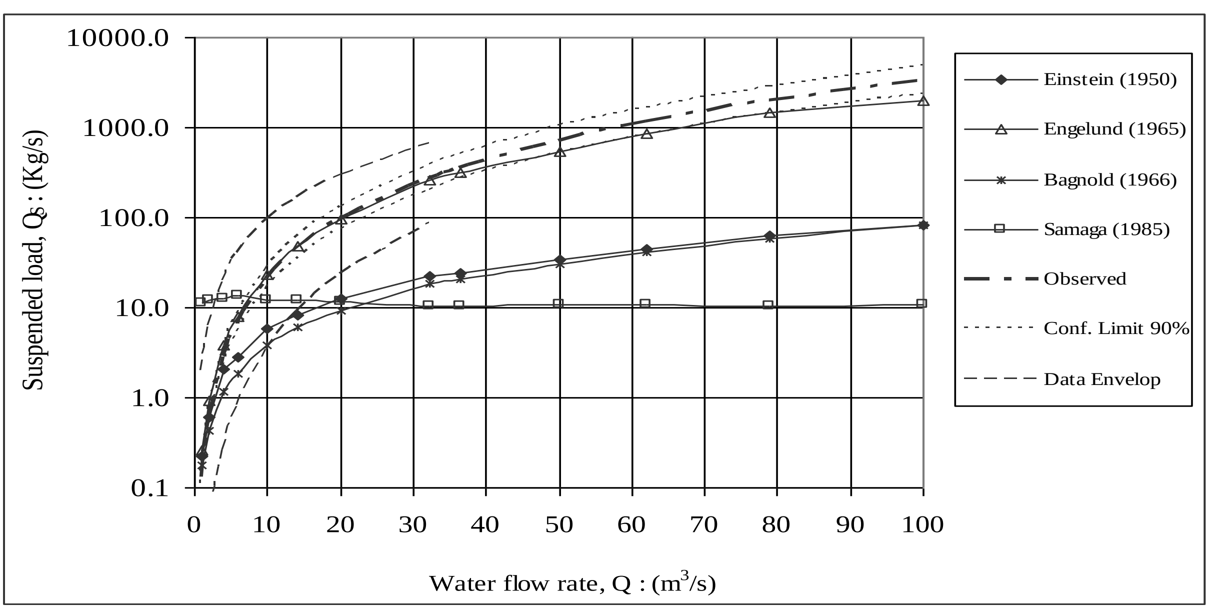

Fig. 1. Evaluation of suspended load (Q_s), using bed-load material, Badalan River Reach

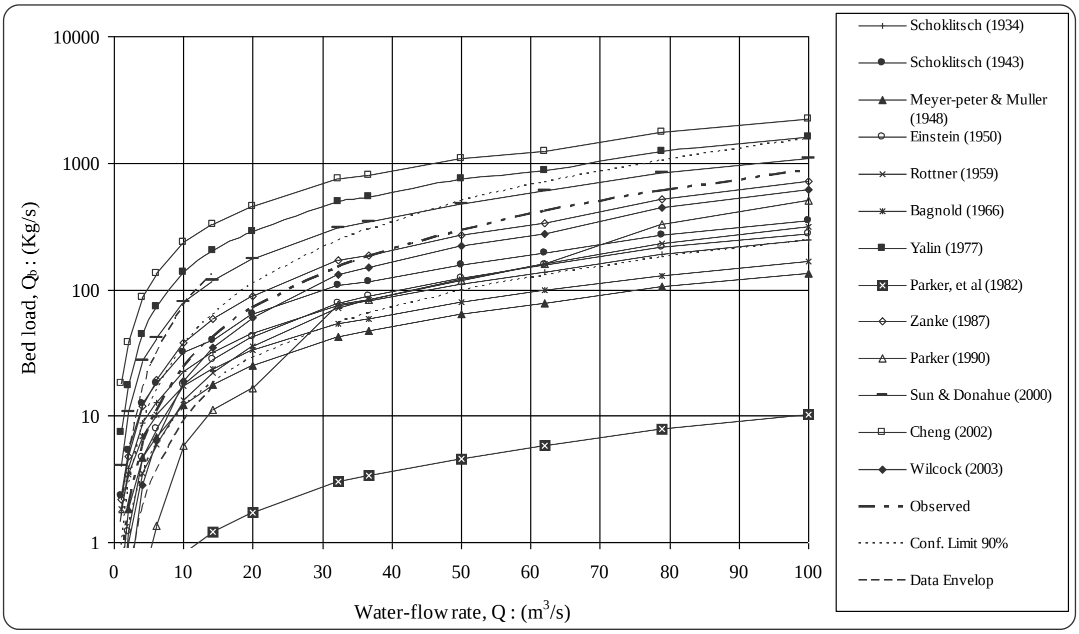

Fig. 2. Evaluation of bed load (Q_b), using bed-load material, Badalan River Reach

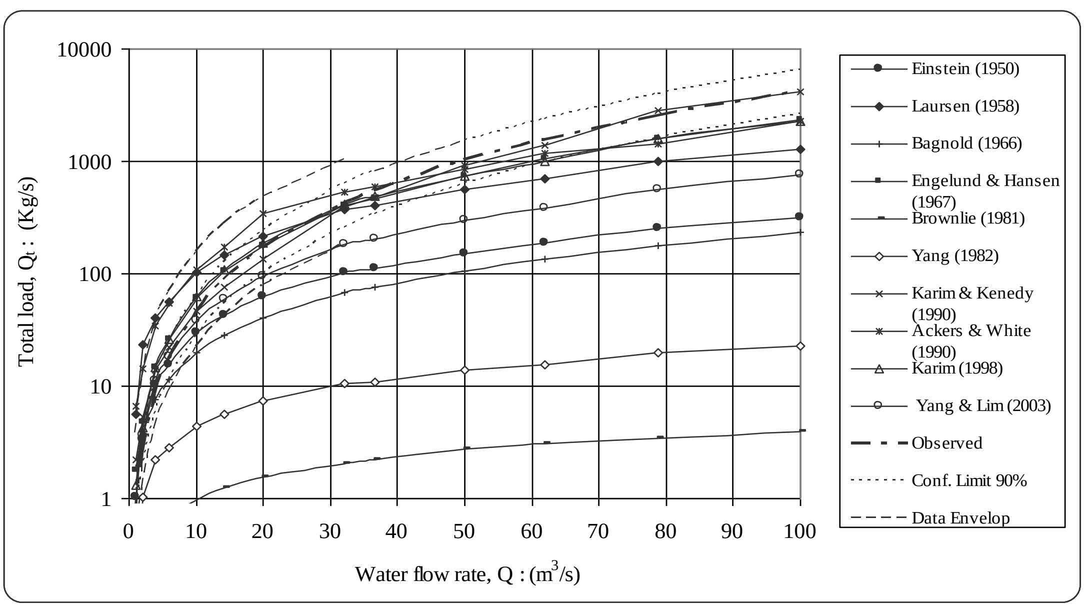

Fig. 3. Evaluation of total load (Q_t), using bed-load material, Badalan River Reach

3. Results and Discussion

Predicted sediment transport rates from the relationships in Table 3 were compared with the corresponding results from the field data, under different flow conditions at four river reaches. Typical detailed calculation of suspended loads are presented in Table 4 and compared with the range of observed data, using the characteristics of surface layer, sub-surface layer and bed-load material. Similar results were provided for bed and total loads, and for the four river reaches.

Table 3. Different sediment transport relationships, applicable to coarse-bed rivers

Methods	Bed Load	Suspended Load	Total Load	Application Remarks
Schoklitsch (1934)	*			Coarse-bed rivers; D= (0.3-5) mm
Schoklitsch (1943)	*			Coarse-bed rivers; D= (0.3-5) mm
Meyer-Peter & Muller (1948)	*			Coarse-bed rivers; D= (0.4-30) mm
Einstein (1950)	*	*	*	Different Rivers
Laursen (1958)			*	Flume Data; D= (0.01-4.1) mm
Rottner (1959)	*			Flumes & Rivers
Engelund (1965)		*		Different Rivers
Bagnold (1966)	*	*	*	Rivers with bed form
Engelund& Hansen (1967)			*	Dune bed form rivers
Yalin (1977)	*			Sand & Gravel bed rivers
Brownlie (1981)			*	Flumes and Rivers
Parker, et al. (1982)	*			Gravel bed rivers, with armoring layer
Yang (1982)			*	Different Rivers
Samaga (1985)		*		Different Rivers
Zanke (1987)	*			Coarse-bed rivers
Ackers& White (1990)			*	Different Rivers, mostly sand-bed
Karim& Kennedy (1990)			*	Different Rivers
Parker (1990)	*			Gravel bed rivers, with armoring layer
Karim (1998)			*	Rivers, without armoring layer
Sun & Donahue (2000)	*			Coarse-bed rivers; D= (2-10) mm
Cheng (2002)	*			Coarse-bed rivers
Wilcock& Crowe (2003)	*			Coarse-bed rivers; D= (0.5-82) mm
Yang & Lim (2003)			*	Sand-bed rivers; D= (0.8-2.2) mm

Table 4. Detailed evaluation of suspended loads (Q_s: kg/s), Badalan River Reach

Bed Layer	Method	Water flow rate, Q: (m^3/s)								
		2	6	10	20	32	50	62	79	100
Surface layer	Einstein (1950)	0	0	0	4	20	32	45	66	179
	Engelund (1965)	0	0	0	0	1	2	3	5	8
	Bagnold (1966)	0	0	1	2	5	7	10	15	20
	Samaga (1985)	1719	2245	2464	2700	2807	2790	2572	2413	2405
Sub-surface layer	Einstein (1950)	0	4	5	11	18	30	40	58	77
	Engelund (1965)	0	3	9	38	106	219	344	580	834
	Bagnold (1966)	0	2	3	7	15	25	33	48	66
	Samaga (1985)	26	28	29	27	26	28	27	25	25
Bed Load Material	Einstein (1950)	1	3	6	13	22	34	44	63	81
	Engelund (1965)	1	8	23	95	262	546	857	1447	1980
	Bagnold (1966)	0	2	4	9	18	31	41	59	82
	Samaga (1985)	12	14	12	12	10	11	11	11	11
Observed		1	7	21	96	273	718	1152	1957	3297
Interval Limit 90%		1	9	27	130	381	1026	1667	2870	4896
		1	5	16	72	202	524	833	1403	2340
Data Envelop		6	39	92	292	644				
		0	1	3	23	87				

Gray area: Uncertain range of data due to the extrapolation of field data

Tables 5 to 7 present an average and the range of relative errors in the evaluation of bed, suspended and total loads with the best fitted relationships among different methods in Badalan River reach using bed-load material characteristics, respectively. Similar results could be demonstrated for the inclusion of either surface layer or sub-surface layer, and for the three river reaches.

This study does not intend to introduce a single relationship for proper prediction of each of the three modes of sediment loads in coarse-bed rivers (i.e. suspended, bed and total loads). The results indicated that such a relationship is impossible to achieve for different reaches and for different flow conditions. Those relationships which are inter-located within the range of field data (or within the general trend of envelope curves of observed data) could be considered as the best fitted predictors. An average and the range of predictive errors give more reliable estimation of sediment load considering uncertainties.

The extent of sediment rating curves, hydrometric data and flow domain were also examined in the Mashiran River reach in order to highlight some uncertainties in the hydrometric evaluation of sediment transport in rivers. The development of the sediment rating curve is presented in Table 8 using five different approaches. Typical result is presented in Figure 4 for the adaption of the Linear method to suspended sediment data. Different values of the sediment rate corresponding to a specific flow rate (Q= 16 m^3/s) are compared in Table 8. The values range widely from 18 to 90 Kg/s, and the selection of the best-fitted method is crucial.

Three statistical measures are provided in Table 8, from which the minimum RMSE value seems to be the best indicator for the selection of sediment rating relationship.

Table 5. Suspended-load prediction error (E%) from selected relationships, Badalan Reach

Predictive Method	Einstein (1950)	Engelund (1965)	Average
Average E%	-75	-1	-38
Range E%	(0) to (-98)	(54) to (-40)	(27) to (-69)

Table 6. Bed-load prediction error (E%) from selected relationships, Badalan Reach

Predictive Method	Schoklitsch (1934)	Schoklitsch (1943)	Rottner (1959)	Zanke (1987)	Parker (1990)	Sun & Donahue (2000)	Wilcock (2003)	Averag e
Average E%	18	42	-43	68	-64	62	-25	32
Range E%	(130) to (-72)	(292) to (-51)	(-62) to (-18)	(215) to (-1)	(-100) to (-37)	(253) to (-22)	(-74) to (-9)	(92) to (-42)

Table 7. Total-load prediction error (E%) from selected relationships, Badalan Reach

Predictive Method	Laursen (1958)	Engelund& Hansen (1967)	Karim&Kenedy (1990)	Akers & White (1990)	Yang & Lim (2003)	Averag e
Average E%	115	10	12	104	-36	36
RangeE%	(373) to (-70)	(-44) to (-88)	(109) to (-19)	(305) to (-45)	(-82) to (-43)	(152) to (-47)

However, it is important to address the sediment yield in the order of prediction intervals of 50%, 75% and 90%. The discrepancies in different confidence limits are depicted from Fig. 4 and Table 9.

The extent of flow domain is also examined by dividing the corresponding flow and sediment data in one and two classes. The results are compared in Table 10 in terms of annual sediment yield.

Table 8. Adaption of sediment-rating curves on suspended sediment data, Mashiran Reach

Method	Linear	Median of Groups	FAO Factor	Parametric Factor	Non parametric Factor
Sediment Load (Kg/s) Q= 16 m^3/s	18	31	90	38	60
R^2 %	44	64	16	74	73
RMSE	690	920	840	460	470
RME	135	94	810	300	520

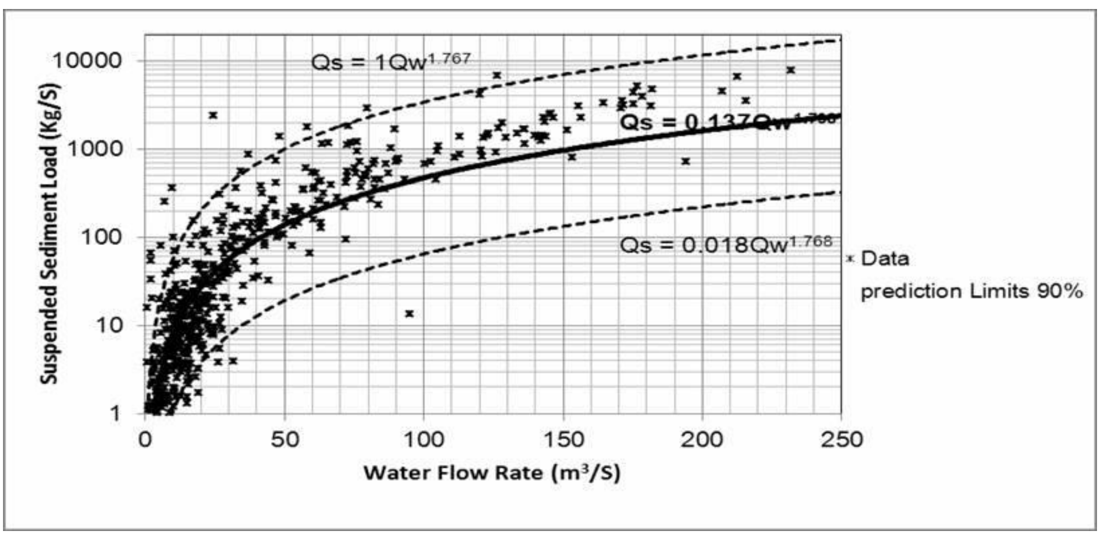

Fig. 4. Sediment-rating curves (mean and 90% envelops of Prediction limits), Mashiran Reach

Table 9. Sediment-rating equation on different Prediction limits, Mashiran Reach

Prediction Domain	Sediment Rating Equations
Average	$Qs = 0.137\ Qw^{1.768}$
90%-Up	$Qs = 1.00\ Qw^{1.767}$
90%-Down	$Qs = 0.018Qw^{1.768}$
75%-Up	$Qs= 0.555Qw^{1.767}$
75%-Down	$Qs = 0.033Qw^{1.768}$

Table 10. Annual sediment yield in different flow domains, Mashiran Reach

Data Set	Flow Rate (m^3/s)	Average (10^3 ton/yr)	90 % Limit : (10^3 ton/yr)	
			Lower	Upper
One Class	($Q_w> 0$)	2200	280	16000
Two Classes	($Qw< 16$) ; ($Qw\geq 16$)	3200	680	13000
Error%		+50%	+140%	-15%

Table 11. Annual sediment yield with different suspended-bed sediment data set, Mashiran Reach

Suspended-Bed Sediment Data	Suspended Load (10^3 ton/yr)	Bed Load (10^3 ton/yr)	Total Load (10^3 ton/yr)
58 (Q_s) – 58 (Q_b)	1300	230	1650
614 (Q_s) & 58 (Q_b)	2200	230	2400
614 (Q_s) &Q_b = 20% Q_s	2200	430	2600
58 (Q_s) &Q_b = 20% Q_s	1300	260	1600

Discrepancies are evident: about 50% in the average value and from 15% to 140% for the 90% prediction limits. The use of bed and suspended sediment data is examined, and the results are presented in Table 11 in terms of annual sediment yield. Four approaches are tested: (1) an equal 58 data set of corresponding data based on the limited available bed load data; (2) 614 suspended and 58 bed sediment data; (3) 614 suspended data and the contribution of bed load as, for example, 20% of suspended load; and (4) 58 suspended data and the contribution of bed load as 20% of suspended load. Discrepancies are evident in Table 11: more than 30% between two tests of 1 and 2, and near 40% between two tests of 3 and 4. It is recommended to use all the available data, and to analyze both suspended and bed loads, separately.

4. Conclusion

The process of flow and sediment transport is different and more complex in coarse-bed rivers than in sand-bed rivers. The main aim of the present study was to evaluate different modes of sediment transport from different hydrometric and hydraulic methods, and to address the major uncertainties.

Results indicated that for most of the relationships, the sediment transport capacity is well described when the characteristics of the bed-load material are included. The inclusion of the sub-surface bed layer into the predictive relationships is considered as the second priority. With the lack of information on bed-material loads in most practical cases, the characteristics of sub-surface bed layer is to be considered as input to the sediment relationships.

This study indicated that the inclusion of surface layer is not appropriate, which is coincident with the previous studies of Wren, et al. (2000), Habersack and Larone (2002) and Almedeij and Diplas (2003).

With the inclusion of bed-load material the overall results indicated that the relationship of Enguelund (1965) gives better predictions in the three river reaches under different flow conditions. The predictive error was estimated to be in the range of -97% to -48% with an average of -77%. When sub-surface layer is included, the calculated suspended loads are reduced in half (by 200%) in average.

For the prediction of bed load, the methods of Schoklitsch (1934, 1943), Rottner (1959), Parker (1990), Zanke (1987), Wilcock (2003) and Sun and Donahue (2000) are more reliable than the others. The predictive error was estimated to be in the range of -58% to +193% with an average of +37%. With the inclusion of sub-surface layer the calculated bed loads are reduced by 10% in average.

For the evaluation of total sediment load, the relationships of Ackers and White (1990), Engelund and Hansen (1967), Yang and Lim (2003), and Karim and Kenedy (1990) resulted in more reliable predictions in the river reaches under different flow conditions. The predictive error was estimated to be in the range of -95% to -48% with an average of -74%. With the inclusion of sub-surface layer, the total sediment loads are reduced by 50% in average.

The previous study indicated that the ratios of bed load to total load in coarse-bed rivers are in the order of 40% to 80%, which are significantly much higher than that in sand-bed rivers.

The overall results indicated that the order of 40% to 70% error is expected, even if using standard sediment measuring system and fitting the measured data to the best predictors. The prediction from the best fitted hydraulic relationships is expected to be in an order of estimation discrepancies between -77% and 200%. An average and the range of predictive values (in the order of prediction intervals of 50%, 75% and 90%) give more reliable estimation of sediment load considering uncertainties in such a complex sediment transporting flow.

The process of hydrometric sediment data are also uncertain in terms of the choice of the sediment rating relationship, the extent of flow domain, and the volume of corresponding bed-suspended sediment data. It is recommended to test the best adaption for the sediment rating curve from five different relationships using statistical measures (in particular RMSE) and with the help of eyes-best fitting approach. It is also important to address the sediment yield in the order of prediction intervals of 50%, 75% and 90%. Division of the flow-sediment data in two classes could be more accurate, providing sufficient data in both classes. It is more appropriate to incorporate all available data and to analyze the suspended and bed sediment yields separately.

The evident discrepancies in the evaluation of the sediment loads are considered to be largely as the results of uncertainties in: (1) the complex process of sediment transport in time by time (in different seasons of a year, and in different years); (2) the unavoidable order of errors in the state of the art of the field measuring devices and techniques; (3) the contribution of wash load; (4) the lack of field sediment data for the range of high flows; and (5) the present state of the hydrometric and hydraulic relationships. These are addressed as major challenges in river engineering.

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Nomenclature

B	Surface water width (m)
C_u	Uniformity coefficient (m/m)
D	Size of bed material (mm)
E	Error
F_r	Froude number
Q	Water flow rate (m^3/s)
Q_s	Suspended load (kg/s)

Q_b	Bed load (kg/s)
Q_t	Total load (kg/s)
R	Hydraulic radius (m)
R^2	Coefficient of determination
RME	Relative mean error
RMS	Root mean square error
S	Energy slope (m/m)
S_g	Specific gravity of bed material
STM	Sediment Transport Model
V	Mean velocity (m/s)
τ	Shear stress (N/m^2)
σ_g	Geometric standard deviation of bed material (m/m)

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