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ABSTRACT

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 (i.e. bed, suspended and total loads) from different methods. Three river reaches were selected as representatives of coarse-bed rivers in North-West of Iran, where observed data were available. A sediment transport model (STM-CBR) was developed to calculate the bed loads from 13 methods, the suspended loads from 4 methods and the total loads from 10 methods. The effects of bed material characteristics were also examined. This paper presents the prediction results and the order of errors for different modes of the sediment loads under different flow conditions. With the inclusion of the order of predictive errors, the best-fitted relationships are recommended for the proper evaluation of different modes of sediment loads in similar coarse-bed river reaches.

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.

Several relationships are available in the literature for predicting sediment transport in coarse-bed rivers, most of which are presented in Table 1. Some of these relationships evaluate the total load directly (e.g. Karim & 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, 1965) or bed load (e.g. Parker, 1990). There is no general guidance to select 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 and reliability of the available relationships (Almedeij and Diplas, 2003; Habersack and Laronne, 2002). However, the order of 50% to 70% error is expected, even when fitting the measured data to the best predictors (van Rijn, 1993).

Table 1. Different sediment transport relationships, applicable to coarse-bed rivers

Methods	Bed Load	Suspended Load	Total Load	Application Remarks
Schoklitsch (1934)	*			D= (0.3-5) mm
Schoklitsch (1943)	*			D= (0.3-5) mm
Meyer-Peter & Muller (1948)	*			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)			*	Rivers; D= (0.8-2.2) mm

Field data on suspended loads are more readily available, although lesser data are taken during high flows. Direct measurements of bed load are difficult to achieve in coarse-bed rivers, and less data is available. Therefore, the evaluation of total sediment load, and the contribution of bed load to the total load are very much 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 & Franzini (1979) suggested that this ratio is to be generally between 10% to 50%, but 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. This ratio was found to be in the range between 0.4 and 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.

The main aim of the present study was to evaluate the different modes of sediment transports from the best fitted hydraulic relationships to the flow conditions in three representative coarse-bed river reaches. The effects of bed material characteristics were also considered in this study.

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). Presence of standard gauging station allowed for simultaneous measurements of bed and suspended loads in each of these three reaches. The Badalan reach is located in a region of 44° 40□ longitude and 38° 34□ latitude, with a length of 150 m. The average bed slope, length to width, and aspect ratios are about 0.007, 8 and 22, respectively. 407 samples of suspended load over a period of 30 years were examined. 77 out of 407 samples include simultaneous measurements of both bed and suspended loads. The Yazdekan reach is located in a region of 44° 47□ longitude and 38° 29□ latitude, with a length of 181 m. The average bed slope, length to width, and aspect ratios are about 0.011, 8 and 25, respectively. 452 samples of suspended load over a period of 15 years were examined. 87 out of 452 samples include simultaneous measurements of both bed and suspended loads. The Baron reach is located in a region of 44° 35□ longitude and 39° 10□ latitude, with a length of 212 m. The average bed slope, length to width, and aspect ratios are about 0.004, 2.3 and 120, respectively. 109 samples of suspended load over a period of 5 years were examined. 57 out of 109 samples include simultaneous measurements of both bed and suspended loads.

River survey, and bed and sediment samplings were carried out. Table 2 presents the characteristics of bed sediments from surface and subsurface layers, and from bed-load samplings in these three reaches. Sediment transport rates (i.e. suspended and bed load, thereby the total load) were evaluated from the field data in different flow conditions. Mean flow characteristics were determined from the calibrated HEC-RAS flow model under different flow conditions in these river reaches, as presented in Table 3. A sediment transport model (STM-CBR) was developed to compute sediment load from different relationships adapted to coarse-bed rivers (the bed load from 13 methods, the suspended load from 4 methods and the total load from 10 methods), as presented in Table 1. The flow characteristics in Table 3 were used as input to the STM-CBR model. As reported by van Rijn (1993), total sediment transport rate was evaluated either by using direct methods (such as: Karim & Kennedy, 1990), or indirectly by summing up the suspended and bed loads calculated from the relationships developed on a similar basis (such as: Einstein, 1950). The effects of sediment characteristics (surface layer, subsurface layer, and bed-load material) were also examined. Relative predictive errors are calculated from the difference between the observed sediment data and corresponding estimated values divided by the observed data.

Table 2. 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	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
(Aland)	Bed load	0.5	0.73	2.5	3.6	7.8	8.6	6	3.3	2.65
Yazdekan	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
(Ghotor)	Bed load	0.7	0.95	3.7	6.4	13.7	20	8.5	4.8	2.65
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
(Baron)	Bed load	0.47	0.6	1.9	2.8	4.8	7	5.3	2.8	2.65

D_s = Charact. Size; C_u = Uniformity Coeff.; σ_g = Geometric Std. Dev.; S_g = Specific Gravity

Table 3. Flow characteristics in three river reaches

Reach (River)	Water flow rate Q (m^3/s)	Mean velocity V (m/s)	Water surface width B (m)	Hydraulic radius R (m)	Energy slope S (%)	Froude No. 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	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	1.44	84.1	0.42	0.81	0.64	33.73
	100	1.82	91.9	0.61	0.68	0.67	40.16
	166	2.19	101.0	0.76	0.78	0.73	58.01

RESULTS AND DISCUSSION

Predicted sediment transport rates from the relationships in Table 1 were compared with the corresponding results from the field data, under different flow conditions at three river reaches. Typical detailed calculation of suspended loads are presented in Table 4 and compared with the range of observed data in different flow conditions, using the characteristics of surface layer, sub-surface layer and bed-load material. Similar results were provided for bed and total loads, in three river reaches.

Figures 1 shows the evaluation of suspended load from 4 relationships, in Badalan river reach, using the characteristics of bed-load sampling material.

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

Bed Layer	Method	Water flow rate, Q: (m^3/s)						
		6	10	20	32	50	62	80
Surface layer	Einstein (1950)	0	0	4	20	32	45	66
	Engelund (1965)	0	0	0	1	2	3	5
	Bagnold (1966)	0	1	2	5	7	10	15
	Samaga (1985)	2245	2464	2700	2807	2790	2572	2413
Sub-surface layer	Einstein (1950)	4	5	11	18	30	40	58
	Engelund (1965)	3	9	38	106	219	344	580
	Bagnold (1966)	2	3	7	15	25	33	48
	Samaga (1985)	28	29	27	26	28	27	25
Bed Load Material	Einstein (1950)	3	6	13	22	34	44	63
	Engelund (1965)	8	23	95	262	546	857	1447
	Bagnold (1966)	2	4	9	18	31	41	59
	Samaga (1985)	14	12	12	10	11	11	11
Observed		7	21	96	273	718	1152	3297
Confidence Limit 90%		9	27	130	381	1026	1667	4896
		5	16	72	202	524	833	2340
Data Envelop		39	92	292	644			
		1	3	23	87			

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

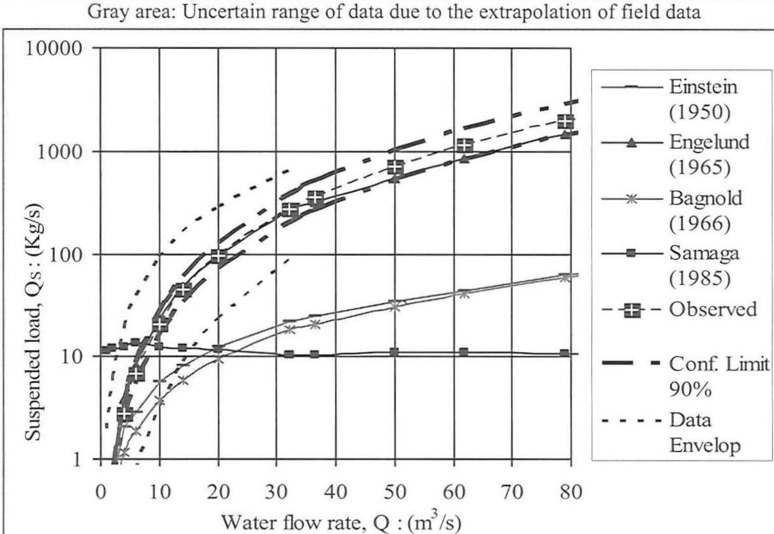

Figure 1. Evaluation of suspended load (Q_s), using bed-load material, Badalan Reach

Similarly, Figures 2 and 3 show the evaluation of bed and total loads, respectively, in Badalan river reach.

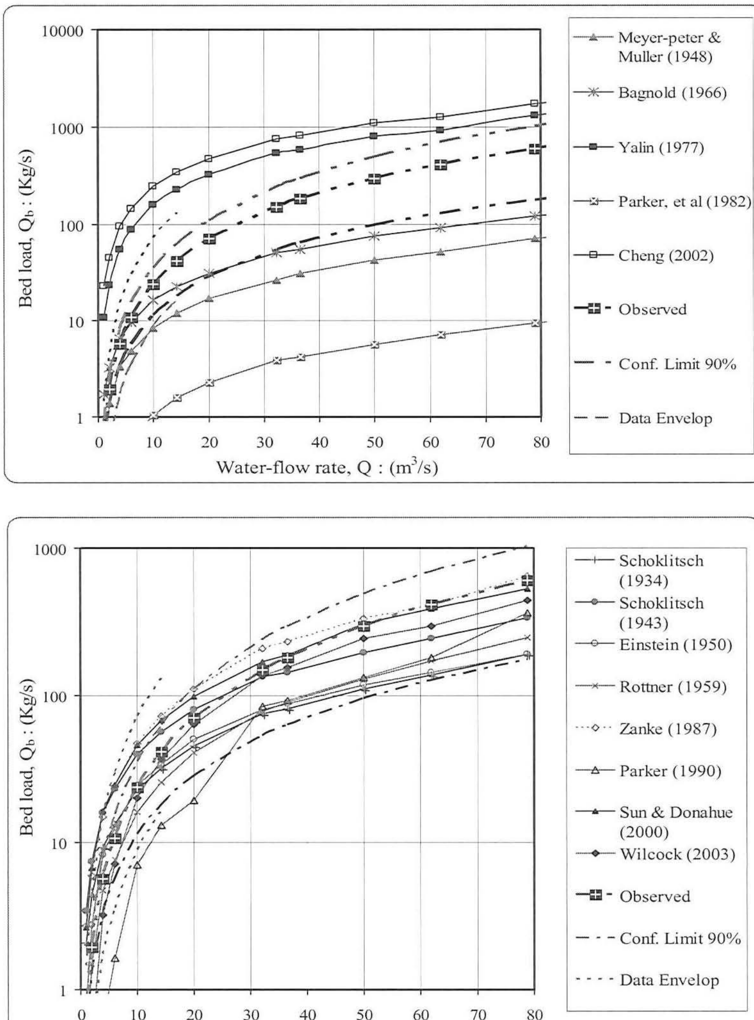

Figure 2. Evaluation of bed load (Q_b), using bed-load material, Badalan River Reach

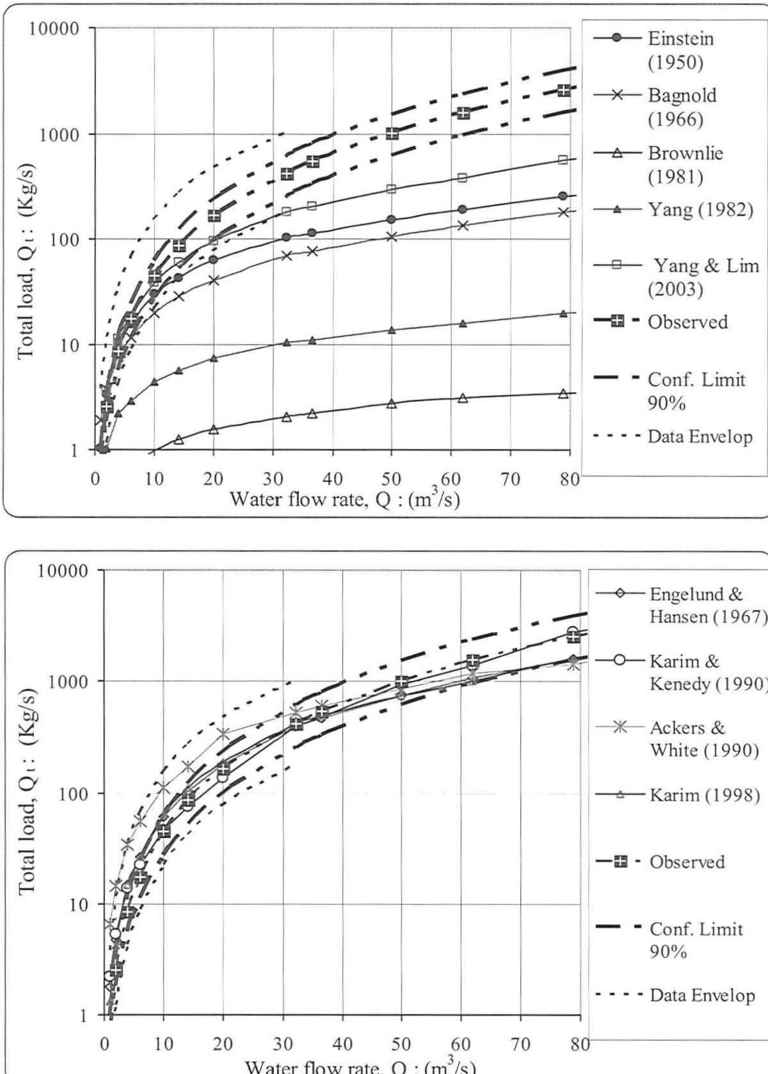

Figure 3. Evaluation of total load (Q_t), using bed-load material, Badalan River Reach

Figures 1 to 3 indicate the prediction of suspended load from 4 relationships, of bed loads from 13 relationships, and of total loads from 10 relationships; also show both the envelop curves and the 90% confidence limits for the range of field data.Similar results could be demonstrated for the inclusion of either surface layer or sub-surface layer, in the three river reaches.

The results indicated that a single relationship is impossible to detect for the prediction of each of the three modes of sediment loads (i.e. suspended, bed and total loads) in different reaches, under different flow conditions. Those relationships which are 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 with the degrees of uncertainties in such a complex problem.

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.

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

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

Predictive	Schk litsch		Rottner	Zanke	Parker	Sun & Donahue	Wilcock	Average
Method	(1934)	(1943)	(1959)	(1987)	(1990)	(2000)	(2003)	
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, using bed-load, material, Badalan River Reach

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

CONCLUSION

The process of flow and sediment transport is different and more complex in coarse-bed rivers than in sand-bed rivers. This study indicated that the sediment transport capacity is well described when the characteristics of the bed-load material are included. With the lack of information on bed-material loads in most practical cases, the characteristics of sub-surface bed layer could be considered as input to the sediment relationships. The inclusion of surface layer is not appropriate for reliable estimation of the sediment transport capacity.

This study does not intend to introduce a single relationship for the 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 located within the range of field data could be considered as the best fitted predictors. As presented in Tables 5 to 7, the average and the range of predictive errors are to be considered for the estimation of sediment load in such a complex problem.

For the prediction of suspended load, the overall results indicated that the relationship of Enguelund (1965) gives better predictions in the three coarse-bed river reaches. With the inclusion of bed-load material, 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 & 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 & White (1990) Engelund & Hansen (1967), Yang & Lim (2003), and Karim & Kenedy (1990) resulted in better 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 in these three coarse-bed rivers indicated that the ratios of bed load to total load are in the order of 40% to 80%, which are significantly much higher than that in sand-bed rivers (Yasi and Hamzepouri, 2008).

The evident discrepancies in the prediction of the sediment loads are considered to be largely as the results of uncertainties in: (1) the present state of the hydraulic relationships; (2) the contribution of wash load; (3) the lack of field sediment data for the range of high flows, and (4) the unavoidable order of errors in the state of the art of the field measuring devices and techniques. These are major challenges in coarse-bed river engineering

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