Feedback between bed load transport and flow resistance in gravel and cobble bed rivers

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[1] To calculate bed load, engineers often use flow resistance equations that provide estimates of bed shear stress. In these equations, on the basis of the estimate of the appropriate hydraulic radius associated with the bed only, the bed roughness k_s is commonly set as a constant, whatever the bed load intensity. However, several studies have confirmed the existence of feedback mechanisms between flow resistance and bed load, suggesting that a flow-dependent bed roughness should be used. Therefore, using a data set composed of 2282 flume and field experimental values, this study investigated the importance of these feedback effects. New flow resistance equations were proposed for three flow domains: domain 1 corresponds to no bed load and a constant bed roughness $k_s = D$ (where D is a representative grain diameter), whereas domain 3 corresponds to a high bed load transport rate over a flat bed with a constant bed roughness $k_s = 2.6D$. Between these two domains, a transitional domain 2 was identified, for which the bed roughness evolved from D to $2.6D$ with increasing flow conditions. In this domain, the Darcy-Weisbach resistance coefficient f can be approximated using a constant for a given slope. The results using this new flow resistance equation proved to be more accurate than those using equations obtained from simple fittings of logarithmic laws to mean values. The data set indicates that distinguishing domains 2 and 3 is still relevant for bed load. In particular, the data indicate a slope dependence in domain 2 but not in domain 3. A bed load model, based on the tractive force concept, is proposed. Finally, flow resistance and bed load equations were used together to calculate both shear stress and bed load from the flow discharge, the slope, and the grain diameter for each run of the data set. Efficiency tests indicate that new equations (implicitly taking a feedback mechanism into account) can reduce the error by a factor of 2 when compared to other equations currently in use, showing that feedback between flow resistance and bed load can improve field bed load modeling.

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1. Introduction

[2] Modeling gravel bed rivers' bed load sediment transport is of primary importance for natural hazards, engineering design, morphodynamics, and ecology. For field applications, the problem consists in calculating a transport rate for given control parameters relative to the channel (geometry and gradient), sediment (river bed or transported material diameters) and flow conditions (discharge, mean depth or mean flow velocity). Bed load is produced by the tractive force exerted by the flow on the bed. One major problem in calculating the appropriate tractive force responsible for bed load is estimating a resistance coefficient representative of the grain roughness only. Several flow resistance relationships were fitted on field data [*Limerinos*, 1970; *Hey*, 1979; *Griffiths*, 1981; *Jarrett*, 1984; *Bathurst*, 2002; *Comiti et al.*, 2007; *Ferguson*, 2007]. These formulations provide the total resistance coefficient and the mean flow velocity at the reach scale but may overestimate the appropriate shear stress required for bed load calculations [*Dietrich et al.*, 1984; *Carling*, 1983; *Petit*, 1989; *Robert*, 1991; *Wilcock and Kenworthy*, 2002; *Rickenmann et al.*, 2006]. Indeed, a natural channel usually exerts a much higher resistance to the flow than the grain resistance alone, because of lateral and vertical channel irregularities, bank and bed vegetation and transported solids. To overcome this problem, a linear decomposition of the resistance coefficient was proposed [*Meyer-Peter and Muller*, 1948; *Einstein and Barbarossa*, 1952], separating the grain resistance coefficient (or friction coefficient) from the coefficients stemming from other causes [*Wilcox and Wohl*, 2006; *Wilcox et al.*, 2006; *Yager et al.*, 2007]. The grain resistance coefficient used for estimating the tractive force was then calculated with laws derived from flow conditions allowing only grain

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resistance (or friction law), usually obtained in flume experiments [*Carling*, 1983; *Wilcock and Kenworthy*, 2002]. For instance, the *Meyer-Peter and Muller* [1948] bed load equation (probably the most widely used for engineering purposes and field investigations today) includes a tractive force correction, i.e., a ratio of grain to total Strickler coefficients, derived experimentally from flows over a fixed bed [*Strickler*, 1923]. Combining two formulas established independently may dissociate the physics of the two phenomena (flow resistance and bed load transport). This can mean that the final relations may not take into account, or at least underestimate, a possible feedback mechanism between bed load and flow resistance. Indeed, since flow resistance is responsible for bed load motion, the bed load may in turn affect flow resistance by modifying the bed roughness. *Meyer-Peter and Muller* [1948] proposed that this effect should be taken into account [*Wong and Parker*, 2006], and more recently, *Yen* [2002] and *Campbell et al.* [2005] recalled the need for a more detailed understanding of the complex feedback mechanisms between sediment transport and flow hydrodynamics in alluvial rivers.

[3] Although a feedback mechanism of this sort has long been suspected, recent studies have clearly demonstrated that, over flat beds, bed load can dramatically increase flow resistance when compared to clear water flows [*Smart and Jaeggi*, 1983; *Rickenmann*, 1990; *Baiamonte and Ferro*, 1997; *Song et al.*, 1998; *Bergeron and Carbonneau*, 1999; *Carbonneau and Bergeron*, 2000; *Omid et al.*, 2003; *Calomino et al.*, 2004; *Gao and Abrahams*, 2004; *Mahdavi and Omid*, 2004; *Campbell et al.*, 2005; *Hu and Abrahams*, 2005]. Some authors [*Engelund and Hansen*, 1967; *Smart and Jaeggi*, 1983] proposed flow resistance and bed load equations derived jointly and implicitly including this type of possible feedback mechanism, but they worked with relatively high-flow conditions, whereas gravel bed river flow conditions are rarely far above incipient motion conditions [*Parker*, 1978; *Andrews*, 1983; *Mueller et al.*, 2005; *Ryan et al.*, 2002; *Parker et al.*, 2007]. Moreover, all authors considered a constant bed roughness k_s for flows with bed load, whereas a feedback effect between bed load and flow resistance suggests that a flow-dependent relation may be required.

[4] Friction factors in an open channel are usually expressed with the Darcy-Weisbach equation:

$$\sqrt{\frac{8}{f}} = \frac{U}{u^*} = \frac{U}{\sqrt{gRS}} \tag{1}$$

where f is the Darcy-Weisbach friction factor, U is the mean cross-sectional flow velocity, R is the hydraulic radius, S is the energy slope and g is the acceleration of gravity. For rough turbulent flows, f can be related directly to the flow's relative roughness R/k_s, the most widely used equation being certainly the Nikuradse-Keulegan equation [*Nikuradse*, 1933; *Keulegan*, 1938]:

$$\sqrt{\frac{8}{f}} = 6.25 + 5.75\log\left(\frac{R}{k_s}\right) \tag{2}$$

The median diameter D_{50} is often used for k_s [*Keulegan*, 1938], but several expressions are given in the literature [*Yen*, 2002]. Especially for graded sediments, and following the Nikuradse equivalent grain roughness concept, k_s is usually assumed to be proportional to a representative sediment size D_x (where subscript x denotes % finer):

$$k_s = \alpha D_x \tag{3}$$

Therefore, all $(8/f)^{1/2}$ expressions found in the literature for rough and turbulent two-dimensional open-channel flows can be summarized by the following general formulation:

$$\sqrt{\frac{8}{f}} = \xi + 5.75\log\left(\frac{R}{D_x}\right) \tag{4}$$

with

$$\xi = 6.25 - 5.75\log\alpha \tag{5}$$

The effects of bed load on flow resistance can be illustrated with these equations. When bed load occurs, the existence of feedback mechanisms suggests that the bed roughness k_s (what is "seen" by the flow) may also depend on the bed load layer's properties (thickness, concentration and velocity) and not only on the sediment diameters. In other words, instead of using a constant α coefficient in equation (3) (as is usually done), a flow-dependent relation could be required. Thus, if α increases with bed load, the consequence would be a decrease in ξ, and hence an increase in the resistance coefficient f (equation (4)).

[5] The objective of this study was to derive, with the same data set, both flow resistance and bed load transport equations jointly taking into account feedback between bed load and flow resistance, and finally to assess whether such equations could improve bed load predictions when compared to existing equations, especially for low-flow conditions.

[6] This study is composed of two steps. The first step consisted of 144 flume experiments with uniform materials, for a wide range of flow conditions (slope, flow and solid discharge), to investigate how bed load affects flow resistance. Experimental results were considered elsewhere [*Recking et al.*, 2008] and are also given by *Recking* [2006]; the main conclusions are reviewed in the next section. In the second step, this data set was extended using data from the literature and was used to derive flow resistance–bed load equations. Because of the problems dissociating all the different contributions to resistance with field data, only data obtained with uniform sediments through flume experiments (1567 values) were used for demonstration. Finally, physical processes involved are discussed and a data set composed of 715 field values is used to investigate the relevance of this research to natural rivers. Slopes steeper or equal to 0.001 are considered.

2. Materials and Methods

2.1. New Data

[7] This section reviews our experimental results [*Recking*, 2006]. Earlier studies on flow resistance usually focused on a single flow condition, for example without bed load [*Keulegan*, 1938; *Song et al.*, 1995] or with moderate bed load [*Meyer-Peter and Muller*, 1948; *Paintal*, 1971; *Cao*,

Table 1. Flow Conditions for Our New Experiments

Parameter	Value
Flume width W, m	0.05, 0.1, and 0.25
Slope S, %	1, 3, 5, 7, and 9
Flow discharge Q, l/s	0.2 to 20
Sediment discharge at equilibrium, g s^{-1} m^{-1}	0 to 1600
Shields number θ	0.01 to 0.29
Froude number Fr	0.5 to 1.83
Reynolds number $Re = UR/\nu$	1900 to 48 000
Roughness Reynolds number $Re^* = u^*D/\nu$	70 to 27 000

1985; *Song et al.*, 1998] or a high bed load transport rate [*Smart and Jaeggi*, 1983; *Rickenmann*, 1990; *Julien and Raslan*, 1998]. However, to investigate the effect of bed load on bed roughness, a data set should be built including both the transition from clear water to bed load and from incipient motion to a high transport rate. Moreover, only a few data were available in the $0.08 < \theta < 0.25$ and $0.01 < \Phi < 0.45$ range for slopes varying from 1% to 9%. θ and Φ are the dimensionless shear stress (or Shields number) and the dimensionless transport rate [*Einstein*, 1950], respectively, and are defined by

$$\theta = \frac{R}{D}\frac{S}{(s-1)} \tag{6}$$

$$\Phi = \frac{q_b}{\sqrt{g(s-1)D^3}} \tag{7}$$

where R is the hydraulic radius [m], S is the bed slope [m m^{-1}], D the sediment diameter [m], s is the ratio of sediment to water density, g is the acceleration of gravity (9.81 m s^{-2}) and q_b is the volumetric solid discharge per unit width [m^3 s^{-1} m^{-1}].

[8] For this reason, we chose to conduct new experiments comparing all flow conditions in this range. The experimental setup consisted in a 10-m-long, 0.05- to 0.25-m-wide tilting flume (slope varying from 1% to 10%). The flow rate at the inlet was ensured by a constant head reservoir and measured by an electromagnetic flowmeter. The sediment feeding system consisted in a customized conveyor belt device ensuring constant feeding. To measure the mean flow velocity, we used a technique very similar to the salt velocity technique [*Smart and Jaeggi*, 1983; *Rickenmann*, 1990] but based on image analysis. This technique consisted of injecting a marker (black ink) into the flow, with two cameras located upstream and downstream of a flume control section taking the measurements [*Recking*, 2006]. It was used to obtain 144 measurements of average mean flow velocities at equilibrium (i.e., when the bed elevation at representative control locations did not move for several hours, with output water and solid discharge constant and equal to input values) with four uniform sediment mixtures (diameter, 2.3 mm, 4.9 mm, 9 mm and 12.5 mm) for a wide range of slopes (1–9%) and flow conditions from clear water to high sediment transport ($0 < \Phi < 0.7$). The choice of uniform distribution was motivated by the necessity to avoid grain sorting that could have prevented a clear analysis of the flow resistance–bed load interactions, but field implications are considered in the discussion. To retain two-dimensional flows, most measurements were taken with a bed width to flow depth ratio, W/H, higher than 3.5 [*Song et al.*, 1995]. Moreover, to calculate appropriate flow resistances, it was necessary to correct the hydraulic radius to take into account a sidewall effect. We used the well-known wall correction procedure proposed by *Johnson* [1942] and modified by *Vanoni and Brooks* [1957]. The flow conditions are summarized in Table 1. The data set and all details concerning experimental conditions are given by *Recking* [2006].

2.2. Data From the Literature

[9] Newly produced data were added to flume experimental data from the literature in the present paper. To restrict the study to the gravel bed configuration, the selection criteria were as follows: (1) measurement at the transport equilibrium flow condition; (2) slope higher or equal to 0.1%; (3) mean diameter higher or equal to 1 mm (except for a few cases concerning sheet flows); (4) no suspension; and (5) no bed forms: for the most part, this concerns dunes, whereas flows with nonbreaking waves on antidune bed forms were assumed not to generate notable additional flow resistance [*Kennedy*, 1960; *Simons and Richardson*, 1966; *Bathurst et al.*, 1982b; *Smart and Jaeggi*, 1983; *Recking*, 2006].

[10] The experimental conditions of the different experiments are summarized in Table 2. All sediments were uniform or nearly uniform. The mean flow velocity was deduced from the mean flow depth (knowing the flow discharge) by *Graf and Suszka* [1987] and by *Brownlie* [1981]. *Cao* [1985], *Smart and Jaeggi* [1983] and *Rickenmann* [1990] used the salt tracer technique.

[11] The entire data set (1736 values) is plotted in Figure 1. Because of the wide range of flow conditions and the lack of information concerning experimental procedures, a qualitative analysis aided in eliminating outliers from the analysis (149 values plotted in gray circles). These data corresponded either to f values that were 50% lower than those calculated with the Keulegan law (equation (2)), considered here as a lower limit, or to very high f values that are not compatible with the flume's flat bed conditions (f higher than predicted by the field equation from *Hammond et al.* [1984], with $k_s = 6.6D$). Other values (approximately 20% of the excluded values) corresponded to a very wide scattering of the data inside a given series of values (when two identical relative depths R/D were associated for the same material and the same slope, with very different mean flow velocities), essentially some of the data produced by *Cao* [1985] on a 1% slope with the 22.2-mm material and *Gilbert* [1914] values on a slope steeper than 2%. More details on this analysis and the entire data set are given by *Recking* [2006]. The resulting data set was composed of 1567 values.

[12] An additional field data set comprising 607 values (Table 3) measured in gravel bed rivers (only slopes steeper than 0.1% were considered) was obtained from *Limerinos* [1970], *Samide* [1971], *Bathurst* [1978], *Hey* [1979], *Griffiths* [1981], *Colosimo* [1983], *Jarrett* [1984], *Bathurst* [1985], *Thorne and Zevenbergen* [1985], *Hey and Thorne* [1986], *Pitlick* [1992], *Andrews* [1994], *MacFarlane and*

Table 2. Flume Data From the Literature

Author	D, mm	σ	ρ_s, t m^{-3}	Slope S, %	W, m	Values	Observation
Cao [1985]	22.2	1.29[a]	2.57	1 to 9	0.6	124	steep slopes
	44.3	1.21[a]	2.75	1 to 9			
	11.5	1.24[a]	2.65	0.5 to 1			
Smart and Jaeggi [1983]	4.3	8.46[b]		3 to 30	0.2	78	steep slopes
	4.2	1.44[b]		5 to 20			
	2	4.6[b]		5 to 20			
	10.5	1.34[b]		3 to 20			
Rickenmann [1990]	10	1.34[b]	2.68	7 to 20	0.2	46	various flow viscosities
Meyer-Peter and Muller [1948]	1.2 to 28.65		1.25 to 4.2	0.3 to 1.7	0.35 to 2	133	from *Smart and Jaeggi* [1983]
Bogardi and Yen [1939]	10.34	1.18	2.63	1.2 to 2.5	0.83	44	as reported by *Brownlie* [1981]
	6.85	1.11	2.61	1 to 2.5	0.83		
	15.19	1.11	2.64	1.1 to 2	0.3		
Casey [1935]	1	1.16	2.65	0.1 to 0.5	0.4	90	as reported by *Brownlie* [1981]
	2.46	2.81	2.65				
Graf and Suszka [1987]	12.2	1.52[b]	2.72	0.75 to 1.25	0.6	114	
	23.5	1.53	2.74	1.5 to 2.5			
Gilbert [1914]	3.17	1.13	2.65	0.8 to 2	0.13 to 0.6	377	as reported by *Brownlie* [1981]
	4.94	1.13	2.65	0.6 to 3			
	7	1.12	2.65	0.7 to 3			
	0.506			0.3 to 2			
Pang-Yung [1939]	1.4	1.96	2.64	0.1 to 0.5	0.4	80	as reported by *Brownlie* [1981]
	2.01	1.9	2.45				
	3.13	2.24	2.49				
	4.36	1.59	2.7				
	6.28	1.49	2.66				
Mavis et al. [1937]	4.18	1.23	2.66	0.1 to 1	0.82	283	as reported by *Brownlie* [1981]
	3.12	1.25	2.66				
	2.03	1.29	2.66				
	1.41	1.24	2.66				
	3.73	1.30	2.66				
	1.68	1.36	2.66				
Paintal [1971]	22.2	1.07	2.65	0.1 to 1	0.91	81	as reported by *Brownlie* [1981]
	7.95	1.1	2.65				
	2.5	1.08	2.65				
Julien and Raslan [1998]	0.2	1.4[b]	2.5	0.19 to 0.42	1.3	28	high R/D, "sheet flow"
	0.6	1.43	2.7	2.57 to 5.11			
	0.4	2.39	2.6	3 to 5.3			
Einstein and Chien [1955]	1.3	1.11	2.65	1.2 to 2.6	0.31	16	as reported by *Brownlie* [1981], high R/D
	0.94						
	0.274						
Sumer et al. [1996]	0.13			0.38 to 0.94	0.3	19	high R/D, "sheet flow"
Kennedy [1961]	0.15	1.3	2.65	0.2–0.25	0.85	16	

[a]Here $\sigma = 0.5(D_{84}/D_{50} + D_{50}/D_{16})$ except for D_{84}/D_{16}.
[b]Here $\sigma = 0.5(D_{84}/D_{50} + D_{50}/D_{16})$ except for D_{90}/D_{30}.

Wohl [2003], *Wohl and Wilcox* [2005], *Mueller et al.* [2005] and *Orlandini et al.* [2006]. It was used with 108 additional values (88 from *Bathurst et al.* [1981] and 20 from *White and Day* [1982]) obtained in a flume experiments over nonuniform sediment mixtures to discuss the relevance of this research to field conditions. The final data set comprises 2282 values.

3. Results

[13] Our flow resistance data were analyzed by *Recking* [2006]. For all slopes considered, we observed that transitions from a clear water flow to a flow with bed load transport, and also from a low bed load transport rate to a high transport rate, were associated with changes in the flow resistance behavior. This made it possible to introduce three flow domains:

[14] 1. Domain 1 is characterized by no bed load; the Darcy-Weisbach resistance coefficient f decreased with increasing relative depth, as commonly predicted by the usual friction laws [*Keulegan*, 1938; *Engelund and Hansen*, 1967].

[15] 2. Domain 2 is characterized by low bed load transport with a noncontinuous and nonuniform bed load layer. Low-relief bed waves were observed that were no more than one grain diameter thick and the wavelength increased when bed load increased (as observed by *Wilcock and McArdell* [1993]), which resulted in a flatter bed as the Shields number increased. In this domain, the resistance coefficient was observed to be constant for a given slope whatever the value of the relative depth R/D, which was interpreted as the result of an additional flow resistance to the clear water flow resistance for increasing R/D (as observed by *Song et al.* [1998]). Because of the inverse correlation between the bed deformation amplitude and the resistance coefficient increase (by comparison with clear water), it was possible to conclude that only the bed load was responsible for this increase in flow resistance (as concluded by *Bathurst et al.* [1982a]).

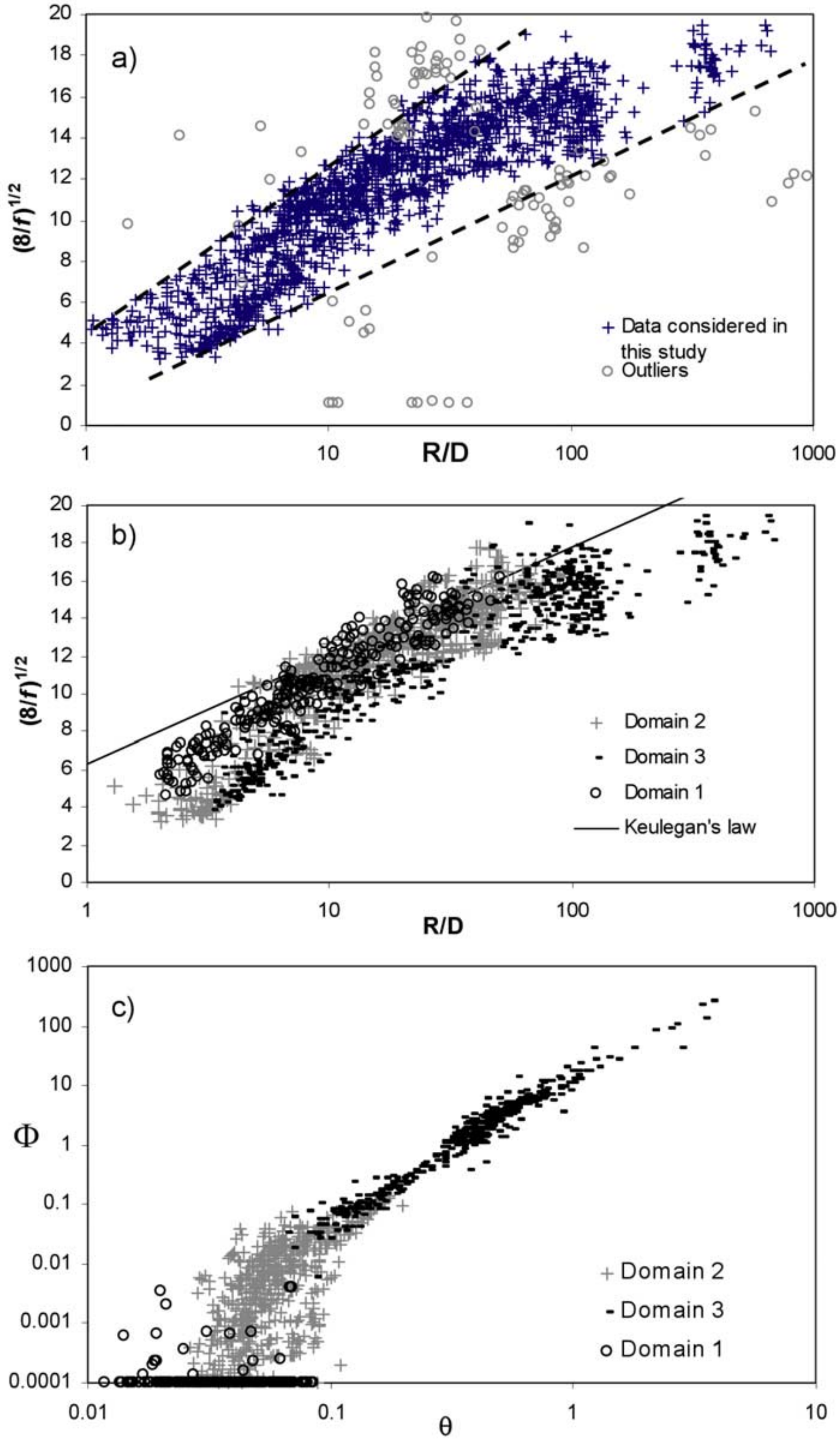

Figure 1. (a) Original data set (1736 values). Outliers (149 values shown by circles) were excluded from the analyses. (b) Flow resistance (R/D,$(8/f)^{0.5}$) and (c) a transport rate (θ,Φ) diagrams with the distinction of belonging to the three flow domains (domain 1, no; domain 2, low; and domain 3, intense transport rate).

Table 3. The 715 Flow Resistance Values (607 Field Values and 108 Flume Values) Corresponding to Flows Over Poorly Sorted Gravels[a]

Author	D_{50}, mm	D_{84}, mm	Slope S	θ/θ_c	Values
Limerinos [1970]	17–152	38–747	?	/	50
Samide [1971]	13–76	NA	0.0015–0.008	1.5–6	55
Bathurst [1978]	170–240	280–485	0.008–0.0174	0.14–0.26	9
Hey [1979]	NA	20–250	0.001–0.031	0.06–2.29	17
Griffiths [1981]	12–301	NA	0.001–0.011	0.06–13	94
Bathurst et al. [1981] flume	8.8–54.25	11.5–58	0.004–0.37	0.06–0.89	88
White and Day [1982] flume	0.25–1.4	0.6–4	0.00045–0.0037	1–4.5	20
Colosimo [1983]	NA	9–662	0.001–0.12	<1	29
Bathurst [1985]	60–343	113–740	0.004–0.037	0.14–1	44
Jarrett [1984]	15–426	792	0.002–0.034	0.051–1.36	75
Thorne and Zevenbergen [1985]	130–167	337–393	0.0143–0.0198	0.4–0.9	12
Hey and Thorne [1986]	14–176	25–624	0.0012–0.21	0.43–4	62
Pitlick [1992]	8–26	33–66	0.0057–0.011	5–11.2	8
Andrews [1994]	58	~100	0.0095–0.011	0.9–1.5	55
MacFarlane and Wohl [2003]	64–181	174–478	0.051–0.14	0.28–0.84	19
Wohl and Wilcox [2004]	38–650	140–1350	0.003–0.24	0.35–4	34
Mueller et al. [2005][b]	27–207	74–1008	0.0005–0.509	0.4–2.17	32
Orlandini et al. [2006]	NA	249–963	0.028–0.181	0.11–0.73	12

[a]Values for θ/θ_c were calculated using D_{50} and equation (22). NA indicates not available.
[b]Bankfull flow conditions; D_{90} instead of D_{84}; only values where D_{90} were available were considered.

[16] 3. Domain 3 is characterized by intense bed load transport over a flat bed with a uniform bed load layer that was several grain diameters thick. The resistance coefficient f was observed to decrease when the relative depth R/D increased, as in domain 1.

[17] In this section, feedback between flow resistance and bed load will be analyzed and modeled with respect to these three flow domains. These effects will be considered in an implicit manner only (the physics involved will be considered in the discussion), by optimizing the fit of several equations for all flow conditions. This will make it possible to quantify the importance of this feedback (by comparison with the commonly used approaches) and to determine whether it is worth being considered in a modeling process.

[18] Because of the problems dissociating all contributions to resistance with field data, only the data obtained in a flume with uniform sediments (Tables 1 and 2) were used for the development. The relevance to natural rivers will be considered in the last section.

3.1. Flow Resistance Modeling

[19] Figure 1b presents the data set including all three domains: flows without sediment transport ($\theta < \theta_c$), flows with a high sediment transport rate and flows with an intermediate transport rate. From preliminary experimental observations, we deduced the condition $\theta > 2.5\theta_c$ as a first approximation to distinguish domains 2 and 3.

[20] These data illustrate that the presence of bed load has a strong effect on flow resistance. Almost all points, particularly those corresponding to flows with high sediment transport, are located below Keulegan's law (equation (8)). Flows without bed load appear to verify Keulegan's law only for a R/D higher than approximately 10.

$$\sqrt{\frac{8}{f}} = 6.25 + 5.75\log\left(\frac{R}{D}\right) \quad (8)$$

The new flow resistance equations proposed were built in two steps: in the first step the new data (limited to slopes greater than or equal to 1%) were used, and in a second step, the model was extended using the entire data set.

[21] The new data (Table 1) were used to fit flow resistance equations that were valid for flows without bed load and flows with high bed load. All intermediate flow conditions (with a moderate transport rate) were analyzed in the second step. Fitting semilogarithmic laws to points measured with a high bed load (flows verifying $\theta > 2.5\theta_c$) gave the following equation:

$$\sqrt{\frac{8}{f}} = -1 + 9.5\log\left(\frac{R}{D}\right)\ \left(r^2 = 0.97\right) \quad (9)$$

For flows without bed load (domain 1), our experiments were considered in the domain $R/D < 8$ because Keulegan's law was assumed to be valid for higher relative depths. The resulting equation is

$$\sqrt{\frac{8}{f}} = 2.5 + 9.5\log\left(\frac{R}{D}\right)\ \left(r^2 = 0.96\right) \quad (10)$$

The transition law between these two equations (domain 2) was approximated by a constant resistance coefficient f for a given slope S (Figure 2), making it possible to fit the following equation:

$$\sqrt{\frac{8}{f}} = -3.7 - 7.18\log(S)\ \left(r^2 = 0.99\right)\ \text{if } S >= 1\% \quad (11)$$

The border between each domain depends on R/D and was estimated from the relation giving the equation intersections in Figure 2, which gives two S power laws, one for the

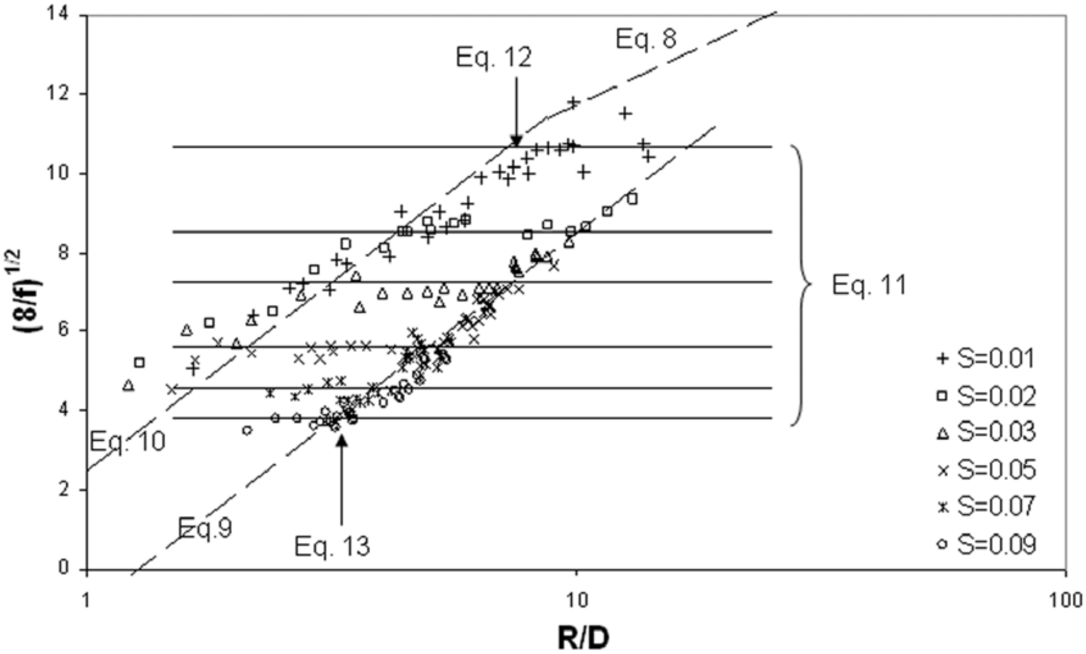

Figure 2. Fit of the transitional law (domain 2) for $S > 1\%$ slopes.

transition from domain 1 to 2 (the intersection between equations (10) and (11)):

$$\left(\frac{R}{D}\right)_{1\rightarrow 2} = 0.223(S)^{-0.756} \text{ if } S >= 1\% \quad (12)$$

and a second law for the transition from domain 2 to 3 (the intersection between equations (9) and (11)):

$$\left(\frac{R}{D}\right)_{2\rightarrow 3} = 0.520(S)^{-0.756} \text{ if } S >= 1\% \quad (13)$$

This fit was only possible because the new data covered all flow domains: no transport, low transport and high sediment transport.

[22] Because the new data were limited to slopes steeper than or equal to 1%, data from the literature were used in an attempt to extend the model to slopes less than 1%. Keulegan's equation (equation (8)) was assumed to be valid for flows without sediment transport on gentle slopes, which is supported by the comparison with the available data. It intercepts the equation for steep slopes (equation (10)) at $R/D = 8.6$.

[23] For flows with high bed load on gentle slopes, the continuity must be verified with the equation established for steep slopes (equation (9)). Moreover, because the data were widely scattered in association with these high-flow conditions, the logarithmic coefficient 5.75 (imposed by the Von Karman value of 0.4) was preserved. This is equivalent to considering that the law established for a fixed bed (equation (4)) is valid, but with a roughness k_s different from the grain diameter D. The result is:

$$\sqrt{\frac{8}{f}} = 3.6 + 5.75\log\left(\frac{R}{D}\right) \ \left(r^2 = 0.78\right) \quad (14)$$

This equation intercepts the steep slope equation (equation (9)) at $R/D = 17$.

[24] The transition law between flows without bed load (domain 1) and flows with a high bed load (domain 3) was fitted for each slope. The continuity must be verified with the equation established for steep slopes (equation (11)). The fitting over 450 data points gave:

$$\sqrt{\frac{8}{f}} = 1 - 4.84\log(S) \ \left(r^2 = 0.86\right) \quad (15)$$

The transition between domains 1 and 2 can be modeled by slope power laws deduced using geometrical considerations. Two equations are required because equation (15) intercepts both equation (8) and equation (10). The intersection between equations (8) and (15) gives (corresponding to $S < 0.7\%$):

$$\left(\frac{R}{D}\right)_{1\rightarrow 2} = 0.135(S)^{-0.841} \ (\text{if } S < 0.7\%) \quad (16)$$

and the intersection between equations (10) and (15) gives (corresponding to $0.7\% < S < 1\%$):

$$\left(\frac{R}{D}\right)_{1\rightarrow 2} = 0.695(S)^{-0.509} \text{ if } 0.7\% < \text{S} < 1\% \quad (17)$$

A last relation was obtained for the transition from domain 2 to 3 (the intersection between equations (15) and (14)):

$$\left(\frac{R}{D}\right)_{2\rightarrow 3} = 0.353(S)^{-0.841} \quad (18)$$

The entire model is presented in Figure 3. The model (equations (8)–(18)) is compared to the data set for the 3%

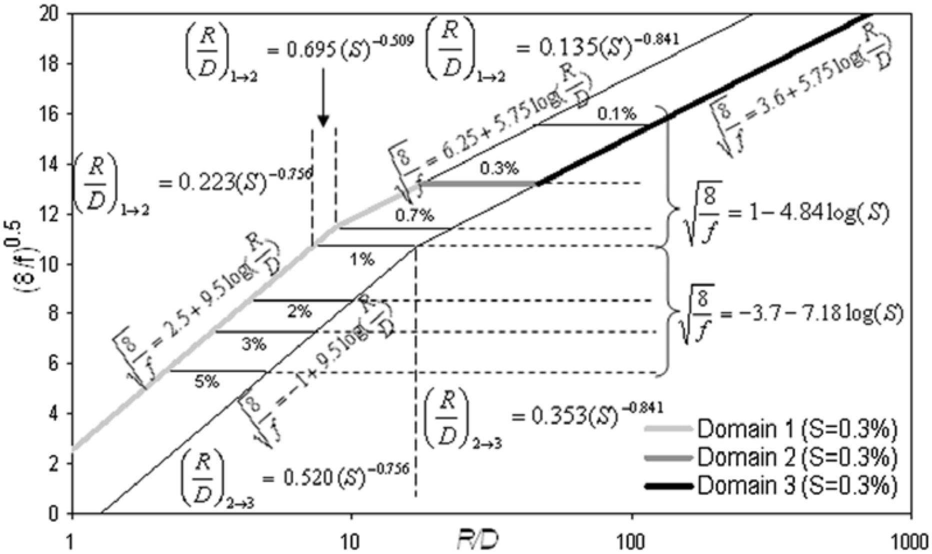

Figure 3. Entire model (bold line represents the model for 0.3% slope).

slope in Figure 4 (all slopes were plotted by *Recking* [2006]).

3.2. Bed Load Modeling

[25] The flow resistance model was used to determine the domain for each run of the data set, knowing the flow discharge Q, the slope S and the grain diameter D. This made it possible to verify whether domains 2 and 3 were still pertinent in terms of solid discharge modeling. The results, presented in the (θ, Φ) diagram of Figure 1c, suggest that the changes observed in grain motion and flow resistance also correspond to a change in the bed load transport rate. Two groups, characterized by a change in the $\Phi(\theta)$ relation shape, can be isolated. The first group (domain 2 runs, in gray in Figure 1c) largely contributed to data dispersion. The second group (domain 3 runs in black in Figure 1c), corresponds to high bed loads and is less scattered.

[26] A semiempirical relationship based on the tractive force concept expressed in the following general form (equation (19)) was used to model bed load:

$$\Phi = A\theta^{\alpha}(\theta - \theta_c)^{\beta} \qquad (19)$$

where θ and Φ are defined by equations (6) and (7), respectively, and ($\theta - \theta_c$) is the excess of the prevailing dimensionless shear stress over the critical incipient motion value θ_c. This equation is very sensitive to the value of θ_c. As the transition from regimes 1 to 2 corresponds to threshold values from which bed load affects flow resistance, using equations (6), (12), (16) and (17), we were able to estimate the corresponding critical Shields

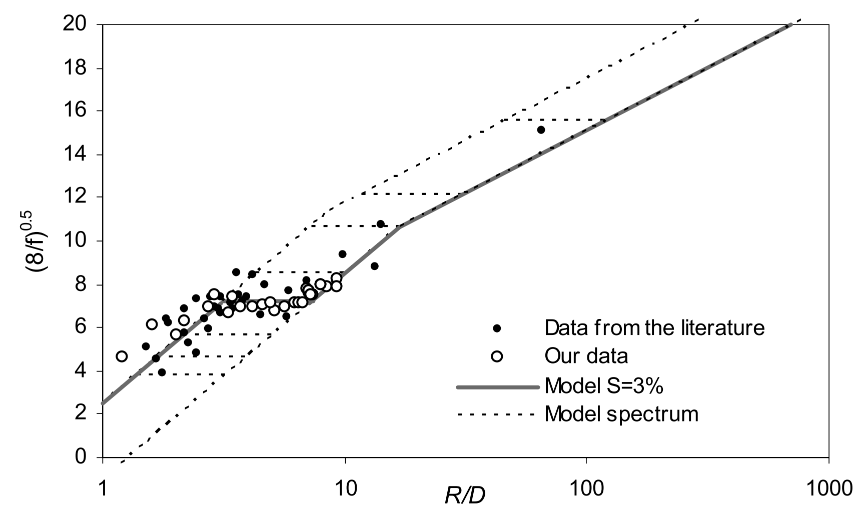

Figure 4. Comparison between data and the flow resistance model (bold line) on slope 3% (horizontal dashed lines represent the model spectrum in domain 2 for slopes 0.1, 0.5, 1, 2, 5, 7, and 9% from top to bottom).

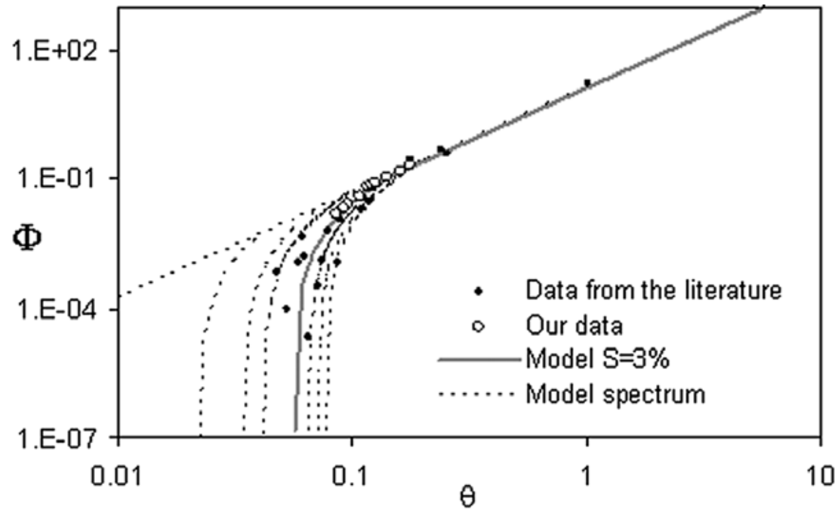

Figure 5. Comparison between data and the bed load model (bold line) on slope 3% (dashed lines represent the model spectrum for slopes 0.1, 0.5, 1, 5, 7, and 9% from left to right).

values. The result was a slope-dependant equation for the critical Shields number θ_c:

$$\theta_c = 0.13S^{0.24} \tag{20}$$

This dependence on the slope was also measured by several authors, both in flume [*Bogardi*, 1970; *Graf and Suszka*, 1987; *Graf*, 1991; *Suszka*, 1991; *Tsujimoto*, 1991; *Aguirre-Pe and Fuentes*, 1991; *Shvidchenko and Pender*, 2000] and in field experiments [*Bathurst et al.*, 1987; *Mueller et al.*, 2005]. Various authors also observed a variation in θ_c with relative depth [*Mizuyama*, 1977; *Torri and Poesen*, 1988; *Lenzi et al.*, 2006].

[27] Equation (20) was used to fit the bed load model. This included two steps. The first step fit equation (19) to the bed load data set by replacing θ_c with equation (20). In the second step, all the coefficients (including those for the θ_c power function) were adjusted to best fit the bed load data set after extrapolation to zero. The best fit of equation (19) was obtained (using an efficiency ratio as defined in the next section) with A = 15.6, $\alpha = 0$, $\beta = 2$:

$$\Phi = 15.6(\theta - \theta_c)^2 \tag{21}$$

The θ_c function was slightly modified:

$$\theta_c = 0.15S^{0.275} \tag{22}$$

Equations (20) and (22) produce the same θ_c values to within ±5%, which is additional evidence that observed changes in flow resistance coincide with the beginning of transport.

[28] The data analysis indicated that the slope effect can be neglected in domain 3 (Figure 1c), which makes it possible to simplify the model by setting $\beta = 0$. The best fit was obtained with A = 14 and $\alpha = 2.45$, which led to the following power law for domain 3:

$$\Phi = 14\theta^{2.45} \tag{23}$$

The limit θ_l between the two models (domains 2 and 3) is slope-dependent and can be approximated by a power law obtained by calculating the intersections between equations (23) and (21) for each slope:

$$\theta_l = 0.65S^{0.41} \tag{24}$$

This Shields number θ_l for the transition from domain 2 to domain 3 produces slightly different results than those obtained considering flow resistance (equations (13) and (18)). In the range $0.004 < S < 0.06$, θ_l is on average equal to $2.5\theta_c$, whatever approach is used, which we suggest as a first approximation. The deviation is higher (up to 20%) for other slopes which can be explained because these equations were obtained from independent fittings and in both cases suffered from imprecision associated with the wide scattering of the data. More research would be necessary to precise these limits.

[29] The bed load model was compared to the data set for the 3% slopes in Figure 5 (all slopes are plotted by *Recking* [2006]).

4. Model Efficiency

[30] In this section, we propose to investigate whether these flow resistance and bed load representations are pertinent when compared to other models. All calculations were made using the known flow discharge *Q*, sediment diameter *D* and slope *S*.

4.1. Comparison Between the Flow Resistance Data Set and the Model

[31] Knowing the flow discharge *Q*, the flume width *W*, the grain diameter *D* and the energy slope *S*, the flow resistance equations (equations (8)–(18)) could be used to calculate the hydraulic radius through iterative calculations and thus were successfully tested ($r^2 = 0.99$) for their ability to reproduce the measured mean flow velocities *U*.

Table 4. Relative Root Mean Square Error for Model Efficiency Comparison for Steep Slopes[a]

	New Model, %	Logarithmic Law From *Cao* [1985], %	Exponential Law From *Smart and Jaeggi* [1983], %
Domain 1 (122 values)	6.8	9.5	10
Domain 2 (349 values)	5.9	9.9	6.6
Domain 3 (136 values)	9.5	12.3	10.2
All data (607 values)	8.1	11.4	9.1

[a]The flow resistance model built from experimental data (equations (9) to (13)) is compared to data from the literature (only slopes steeper than 1% are considered).

[32] The model's efficiency was tested on the entire data set and compared to other models by calculating a relative root mean square error (RRMSE) defined by

$$RRMSE = \frac{\sqrt{\bar{\varepsilon}^2 + \sigma_\varepsilon^2}}{\overline{U_{mes}}} \tag{25}$$

where ε is the error calculated from the difference between the measured and calculated values of U and σ_ε is the standard deviation of ε.

[33] First, for independent verification, the model built with the new data (equations (9)–(13)) was verified on the data from the literature, for slopes steeper than 1% and relative depths lower than 15 (607 values). The semilogarithmic model proposed by *Cao* [1985] and the exponential model from *Smart and Jaeggi* [1983] were also used for the comparison, as they were proposed for similar flow conditions. Actually, it should be noted that the Smart and Jaeggi equation was initially derived for calculations with the flow sediment mixture depth H_m, which can be significantly different than the clear water depth H for flows with high bed load transport on very steep slopes ($S > 10\%$). The results (Table 4) indicate that the new approach, which considered bed load, reduces mean error by 3% compared to a simple logarithmic law. Smart and Jaeggi's model, taking into account the change on steep slopes, gives an intermediate result between the other two.

[34] A second step consisted in testing the model for all slopes and on the entire data set (1551 values). This time, the model was compared with models from *Cao* [1985] and *Smart and Jaeggi* [1983], but also with models proposed by *Keulegan* [1938] and *Strickler* [1923], the roughness being defined by $K_s = 21.1D^{-1/6}$ [*Graf and Altinakar*, 2000]. The results obtained with the slope-dependent model (Table 5) were much better when taking into account the wide data scattering associated with the experimental data, especially for the low transport rate regime. However, overall these results confirm that a law established for flows over a fixed bed on gentle slopes [*Keulegan*, 1938] is not appropriate for flows with bed load, especially when used on a steep slope. Indeed, an 18.7% RRMSE difference was calculated between the two model efficiencies.

4.2. Comparison Between the Bed Load Data Set and the Model

[35] To evaluate the accuracy of the computed values, a discrepancy ratio r was used, defined as

$$r = \Phi_{computed} / \Phi_{Calculated} \tag{26}$$

The model was tested on the entire bed load data set, totaling 1270 values. Models from *Meyer-Peter and Muller* [1948], *Smart and Jaeggi* [1983], *Engelund and Hansen* [1967], *Engelund and Fredsoe* [1976], *Rickenmann* [1991, 2001], *Abrahams and Gao* [2006], and *Brown* [1950], completed by *Julien* [1995, 2002], *Graf and Suszka* [1987], *Schoklitsch* [1962], modified by *Bathurst* [1987], and *Parker* [1979], were also used for the comparison. The model from *Julien* [2002] was tested only for domain 3 because it was proposed for $\theta > 0.1$. For very steep slopes ($S > 10\%$), equations from *Smart and Jaeggi* [1983] and *Rickenmann* [1991] should rigorously be tested using the mixture flow depth (water plus sediment) instead of the clear water depth, but this was not done because here it concerns less than 4% of the total bed load data set.

[36] Table 6 presents the percentages of r ratios obtained in the intervals [$0.8 < r < 1.2$], [$0.6 < r < 1.4$] and [$0.5 < r < 2$]. For instance, the values given in the [$0.8 < r < 1.2$] interval represent the percentage of runs that were correctly reproduced by the model with a precision of ±20%. For each

Table 5. Relative Root Mean Square Error for Flow Resistance Model Efficiency Comparison

	New Model, %	*Keulegan* [1938], %	*Cao* [1985], %	*Smart and Jaeggi* [1983], %	*Strickler* [1923], %
No bed load, $R/D < 8.6$ (domain 1, equation (10), 125 values)	7.2	13.4	9.2	10.9	14.4
No bed load, $R/D > 8.6$ (domain 1, equation (8), 74 values)	5.2	5.2	11.3	5.8	11.8
Low bed load, $S > 1\%$ (domain 2, equation (11), 312 values)	6.5	22.0	11.9	8	19.9
Low bed load, $S < 1\%$ (domain 2, equation (15), 490 values)	4.4	6.4	8.4	4.6	10
Intense bed load, $R/D < 17$ (domain 3, equation (9), 224 values)	9.5	28.2	13.6	11.2	20.1
Intense bed load, $R/D > 17$ (domain 3, equation (14), 342 values)	9.1	17.1	10.2	13.9	9.1
All data (1567 values)	8.0	20.5	11.4	10.7	15.7

Table 6. Scores for Each Model in Three Ranges, With $r = \Phi_{calculated}/\Phi_{measured}$[a]

Model	$0.8 < r < 1.2$	$0.6 < r < 1.4$	$0.5 < r < 2$
	Domain 2 (746 Values)		
MPM/*Strickler* [1923]	3/8	7/13	19/27
Smart and Jaeggi [1983]	10/12	19/22	30/34
Engelund and Hansen [1967]	9/9	20/19	32/32
Engelund and Fredsoe [1976]	3/NA	5/NA	9/NA
Brown [1950] and *Julien* [1995]	9/10	22/23	36/45
Julien [2002]	NA	NA	NA
Graf and Suszka [1987]	14/NA	26/NA	34/NA
Schoklitsch [1962]	NA/15	NA/28	NA/38
Rickenmann [2001]	NA/11	NA/26	NA/34
Rickenmann [1991]	14/20	24/30	35/40
Abrahams and Gao [2006]	17/NA	26/NA	34/NA
Parker [1979]	10/NA	19/NA	35/NA
New model	**23/25**	**40/40**	**53/54**
	Domain 3 (524 Values)		
MPM/*Strickler* [1923]	19/30	51/60	73/75
Smart and Jaeggi [1983]	20/22	35/38	46/49
Engelund and Hansen [1967]	10/15	32/39	49/54
Engelund and Fredsoe [1976]	17/NA	34/NA	57/NA
Brown [1950] and *Julien* [1995]	28/10	53/21	79/72
Julien [2002]	32/NA	50/NA	66/NA
Graf and Suszka [1987]	15/NA	45/NA	66/NA
Schoklitsch [1962]	NA/10	NA/20	NA/29
Rickenmann [2001]	NA/15	NA/32	NA/38
Rickenmann [1991]	19/25	31/41	41/50
Abrahams and Gao [2006]	29/NA	50/NA	75/NA
Parker [1979]	32/NA	55/NA	79/NA
New model	**40/55**	**74/83**	**89/94**
	All Data (1270 Values)		
MPM/*Strickler* [1923]	10/17	25/32	41/46
Smart and Jaeggi [1983]	14/16	26/29	37/40
Engelund and Hansen [1967]	9/11	25/27	39/41
Engelund and Fredsoe [1976]	9/NA	17/NA	29/NA
Brown [1950] and *Julien* [1995]	17–10	35–22	54/56
Julien [2002]	NA	NA	NA
Graf and Suszka [1987]	14/NA	34/NA	47/NA
Schoklitsch [1962]	NA/13	NA/24	NA/34
Rickenmann [2001]	NA/13	NA/28	NA/36
Rickenmann [1991]	16/22	27/35	37/44
Abrahams and Gao [2006]	22/NA	36/NA	51/NA
Parker [1979]	19/NA	34/NA	53/NA
New model	**30/37**	**54/58**	**68/70**

[a]Scores are given in percent. Two values are associated with each case: The left value was obtained with the Shields number θ deduced from the measured mean flow velocities U given in the data set (test of the bed load model only). The right value was obtained with θ calculated from the flow discharge Q, the slope S and the grain diameter D, when a friction equation was provided by authors.

interval considered, the higher the value was, the better the model was. Two values were systematically proposed. The left value was obtained with the Shields number θ deduced from measured mean flow velocities given in the data set, so that only the bed load model could be tested. The right value was obtained with θ calculated from the flow discharge Q, the slope S and the grain diameter D, when the authors proposed a friction equation with the bed load equation (test of the friction and bed load equations together). The equation from *Meyer-Peter and Muller* [1948] was tested with the Manning-Strickler friction law by defining roughness with $K_s = 21.1/D^{1/6}$ [*Graf and Altinakar*, 2000]. Equations from *Schoklitsch* [1962] modified by *Bathurst* [1987], as well as the equation from *Rickenmann* [2001], allowed a direct calculation of the unit solid discharge q_b from the unit flow discharge q (no shear stress calculation). The comparison between measured and calculated transport rates is presented in Table 6.

[37] Bed load transport models developed in this study greatly improved the bed load prediction (by nearly a factor of 2 in comparison with nearly all the models tested). The best fit of the data set is likely to originate in the use of different equations for each flow domain rather than in a real gain into the physics of bed load transport, but consideration of bed load and flow resistance interactions also contributed to improve prediction. Indeed, scores were improved when calculations were made with θ deduced from Q, S and D (using the flow resistance equations) instead of θ deduced from the mean flow velocity measurements. This can be explained because Q, S and D are well-known values imposed in the experiments, whereas measurement of the mean flow velocity can contribute to scattering the data somewhat. This suggests that the friction

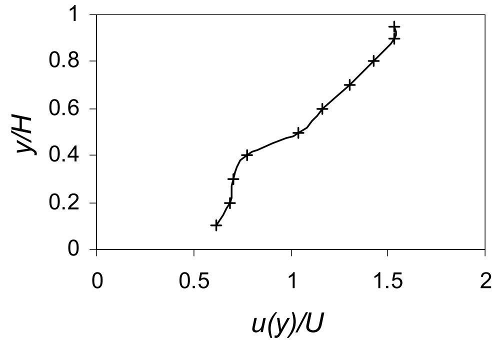

Figure 6. Velocity profile measured over gravel bed (data from *Marchand et al.* [1984]) (Lake Creek).

law proposed in this study allows a confident estimation of the bed shear stress. Indeed, when the new bed load model was used alone with Keulegan and Manning-Strickler flow resistance equations, the scores were reduced by a factor of 2 (becoming 14% and 15%, respectively within the range [$0.8 < r < 1.2$]).

[38] This illustrates that bed load and flow resistance equations should be investigated together to take all feedback effects into account (in an implicit manner), as hypothesized. Although the models proposed in this study and the data set were not totally independent, it is important to note that the same models reproduced bed load values from 15 different authors, whatever the flow condition, bed slope and sediment diameter. One could object that these improved results simply stem from the use of several flow resistance equations instead of a single equation. However, it must be remembered that our proposed resistance and bed load equations were broken down according to the three domains identified (no bed load, low bed load and high bed load). This could only be initially evidenced by our own data set covering all three domains.

5. Discussion

[39] The models presented in the previous sections are the best adjustments that could be obtained when considering each flow condition, but do not provide an explanation of the physical processes involved, which will be discussed now. Two main features are nonvalidity of Keulegan's law when relative depths are lower than approximately 10 and higher flow resistance when flows occur over a bed load layer, whatever the slope.

5.1. Roughness Layer Effects on Steep Slope and Low Relative Depth Flows

[40] The need to distinguish between low and high relative depths was confirmed by several studies from both flume [*Graf*, 1991; *Smart and Jaeggi*, 1983] and field experiments [*Day*, 1977; *Rickenmann*, 1994; *Bathurst*, 2002; *Ferguson*, 2007]. This should be discussed considering the flow turbulence properties. Keulegan's equation was obtained by integrating the Prandtl-Karman logarithmic mean flow velocity profile equation (valid for the inner region) over the entire flow depth and was fitted for rough flow experiments conducted over fine and homogeneous fixed roughness. If it is commonly admitted that the logarithmic profile can be extended to the free surface in flows over gravel beds [*Graf and Altinakar*, 2000], measurements indicate that it cannot be extended to the rough bed [*O'Loughlin and Annambhotla*, 1969; *Christensen*, 1971; *Ashida and Bayazit*, 1973; *Mizuyama*, 1977; *Day*, 1977; *Nowell and Church*, 1979; *Marchand et al.*, 1984; *Nakagawa et al.*, 1988; *Bathurst*, 1988; *Jarrett*, 1990; *Aguirre-Pe and Fuentes*, 1990; *Robert*, 1991, *Wiberg and Smith*, 1991; *Tsujimoto*, 1991; *Pitlick*, 1992; *Ferro and Baiamonte*, 1994; *Byrd et al.*, 2000; *Byrd and Furbish*, 2000; *Nikora et al.*, 2001; *Katul et al.*, 2002; *Franca*, 2005]. Instead, a more complicated profile was described ('s-shaped' profile), made up of a first zone close to the bed (called the roughness layer or wake zone), where the mean velocity is nearly uniform and a second zone located above it, where the logarithmic velocity function is valid (Figure 6). The roughness layer results from interactions between the main flow and the bed roughness. More precisely, two sublayers were considered [*Nowell and Church*, 1979; *Nikora et al.*, 2004], with a first zone corresponding to the flow below the top of roughness elements and essentially controlled by the roughness density and form drag induced by each element, and a second zone, above it, produced by the wakes shed from roughness elements. In this wake zone, a portion of the kinetic energy of the mean flow is transformed into turbulence energy in zones of intense shear downstream from the leading edge of each element (Kevin-Helmoltz instabilities), with this turbulence intensifying the mixing or transfer of momentum, resulting in a continuous adjustment in the velocity profile close to the bed. When fitting the logarithmic flow resistance equation (equation (2)) (used to extend to results obtained on gentle slopes), to this profile, this is equivalent to approximating the s-shaped velocity profile with the Karman-Prandtl logarithmic function, and the only possible variable becomes the Nikuradse equivalent roughness through the coefficient $\alpha = k_s/D$ (equation (5)). The resulting flow resistance equation will thus be closely dependent on the turbulent roughness layer's properties.

[41] The roughness layer's properties are, however, poorly documented. Turbulence intensity was observed to depart from that described for a smooth bed (as described by *Nezu and Nakagawa* [1993]) close to the bed, with a peak located at a distance approximately equal to $0.1-0.2\ H$ above the bed and a decrease toward the bed [*Bayazit*, 1976; *Wang et al.*, 1993; *Dittrich and Koll*, 1997; *Carollo et al.*, 2005]. *Nowell and Church* [1979] measurements indicate that it corresponds to a very high dissipation rate balanced by local production. Although all authors agree that in that zone the velocity profile is different from the profile for the main flow, it was assumed to be constant [*Aguirre-Pe and Fuentes*, 1991] or linear [*Nikora et al.*, 2001]. The roughness layer thickness is on the order of magnitude of the grain diameter and was described between 0.3 [*Nowell and Church*, 1979; *Aguirre-Pe and Fuentes*, 1990] and one grain diameter [*Tsujimoto*, 1991; *Carollo et al.*, 2005]. Actually, several studies confirm that numerous parameters can influence the roughness layer development such as the grain shape [*Gomez*, 1993], the grain concentration [*Nowell and Church*, 1979; *Carollo et al.*, 2005] or momentum exchanges between surface and subsurface flows [*Nakagawa et al.*, 1988]. In particular, an optimum concentration of protruding

sediments (the ratio between the number of grains and the maximum number of grains that can be arranged in the reference area) was observed over which the roughness layer effects were described to stabilize [*Carollo et al.*, 2005] or even to decrease by bed smoothing [*Nowell and Church*, 1979]. However, available measurements indicate that the roughness layer still exists above a maximum concentration, i.e., above a gravel bed of uniform sediment distribution [*Aguirre-Pe and Fuentes*, 1990; *Tsujimoto*, 1991; *Manes et al.*, 2007]. The most interesting result that should be considered here is that the turbulence intensity of the roughness layer was observed to increase with decreasing relative depth [*Bayazit*, 1976; *Wang et al.*, 1993; *Dittrich and Koll*, 1997; *Carollo et al.*, 2005] and increasing slope [*Tsujimoto*, 1991]. This can be explained because the wake's frequency and size depend on the mean flow velocity [*Nowell and Church*, 1979], which is increased with increasing slope for a given relative depth, and are controlled in the upper part by the turbulent mixing of the logarithmic zone [*O'Loughlin and Annambhotla*, 1969], whose importance is also assumed to decrease with decreasing relative depth [*Nikora et al.*, 2001].

[42] The more the relative depth decreases, the more the flow turbulence is affected by the wake zone. Thus, when fitting the logarithmic function equation (2) on measured mean flow velocities, turbulence modifications will necessarily affect the only possible variable that is the equivalent Nikuradse roughness $k_s = \alpha D$, which also becomes a function of R/D. As a consequence, the logarithmic coefficient 9.5 obtained from the low relative depth data (equation (10)) would correspond to a progressive downward shift of equation (2) because of varying values $k_s = \alpha(R/D)D$ when the velocity profile deviates from the logarithmic function with decreasing R/D. Keulegan's equation corresponds to $\alpha = k_s/D$ equal to 1 and we deduce from equation (9) and equation (2) an increase to approximately 4 when R/D tends to 1. In this study, we considered a deviation from Keulegan's law at R/D equal to 8.6, but this abrupt change was obtained arbitrarily from the authors' measurements for modeling purposes, and a more progressive deviation may be expected. For instance, *Graf* [1991] suggested a progressive variation that would occur from $R/D = 25$. Fitting a power law on $1 < \alpha < 4$ in the range $25 > R/D > 1$ gives

$$\alpha_{RL} = 4\left(\frac{R}{D}\right)^{-0.43} \text{ with } 1 \leq \alpha_{RL} \leq 4 \quad (27)$$

Subscript *RL* denotes roughness layer. This function reproduces adequately ($r^2 = 0.96$) the flow resistance data (without sediment transport) when used in equation (2). For such flows, a power function is adequate to model flow resistance [*Bathurst*, 2002], and *Ferguson* [2007] proposed varying power coefficients according to R/D (in much the same way as k_s/D was described to vary with R/D in this paper). The logarithmic function is interesting because it permits a direct comparison with gentle slope results which are usually expressed with a logarithmic function.

[43] The near-bed velocity profile affects both drag and lift forces exerted at the grain [*Wiberg and Smith*, 1987], with consequences on incipient motion conditions. As the roughness layer turbulence intensity is increased with decreasing relative depth and increasing slope, it produces a local near-bed velocity profile that is increasingly uniform [*Tsujimoto*, 1991], which could explain the variation of θ_c with slope. This led *Tsujimoto* [1991] to postulate that the effect of slope on $\theta_c = \Psi_1(S)\Psi_2(S)$ is composed of two parts: $\Psi_1(S)$ as an effect of gravity itself and $\Psi_2(S)$ as an effect of degeneration of velocity distribution due to small relative depth. The former is a decreasing function of *S* while the latter is an increasing one. The resulting function was observed to be an increasing one (equation (20)). These opposite influences of decreasing relative depth and simultaneously increasing slope were successfully reproduced with an analytical model by *Vollmer and Kleinhans* [2007].

5.2. Bed Load Roughness Layer

[44] The second important result to be discussed is that bed load increases flow resistance. This has been demonstrated experimentally by many researchers over the last 10 years [*Smart and Jaeggi*, 1983; *Rickenmann*, 1990; *Baiamonte and Ferro*, 1997; *Song et al.*, 1998; *Bergeron and Carbonneau*, 1999; *Carbonneau and Bergeron*, 2000; *Omid et al.*, 2003; *Calomino et al.*, 2004; *Gao and Abrahams*, 2004; *Mahdavi and Omid*, 2004; *Campbell et al.*, 2005], and the generally accepted view is that bed load extracts momentum from the flow, which causes a reduction in flow velocity and increases the apparent roughness length in proportions that are related to the thickness of the moving sediment layer [*Owen*, 1964; *Dietrich*, 1982; *Wiberg and Rubin*, 1989]. In addition, the wakes that are shed as sediment grains are accelerated by the flow produce a roughness layer that develops well beyond the top of the saltation layer, affecting the mean velocity profile [*Bergeron and Carbonneau*, 1999; *Carbonneau and Bergeron*, 2000], in a similar way to what was described for fixed beds on steep slopes. *Campbell et al.* [2005] showed that it corresponds to a zone of intense turbulent kinetic energy production, whose thickness would increase essentially with the sediment size. Increasing concentration was observed to affect the mean velocity profile inside the roughness layer, but not the roughness layer thickness (but only two cases were considered). When the bed load transport was very high (sheet flow), *Sumer et al.* [1996] measured a power velocity function inside the bed load layer.

[45] If the mean flow velocity profile is affected by momentum extraction and the wake shed by accelerating grains as the bed load transport rate is increased, and considering that bed load increases with the Shields number $\theta = RS/[(s-1)D]$, for a given energy slope *S* the fitting of equation (2) is likely to increase the equivalent bed roughness $k_s = \alpha_{BR}D$ (subscript *BR* denotes bed load roughness) as relative depth R/D increases. Consequently, the constant resistance coefficient *f* proposed for a given slope (equation (15)) would also be an artifact that would correspond to a progressive downward shift of equation (2) when relative depth increases. The function $\alpha_{BR}(R/D)$ can be investigated based on gentle slope data, for which the roughness layer described for a fixed bed is considered negligible ($\alpha_{RL} \approx 1$). Considering a variation of α_{BR} between 1 for clear water flows (Keulegan's law) and $\alpha_{BR} = 2.6$ (deduced from equations (2) and (14)) for high bed load transport when relative depth increases between

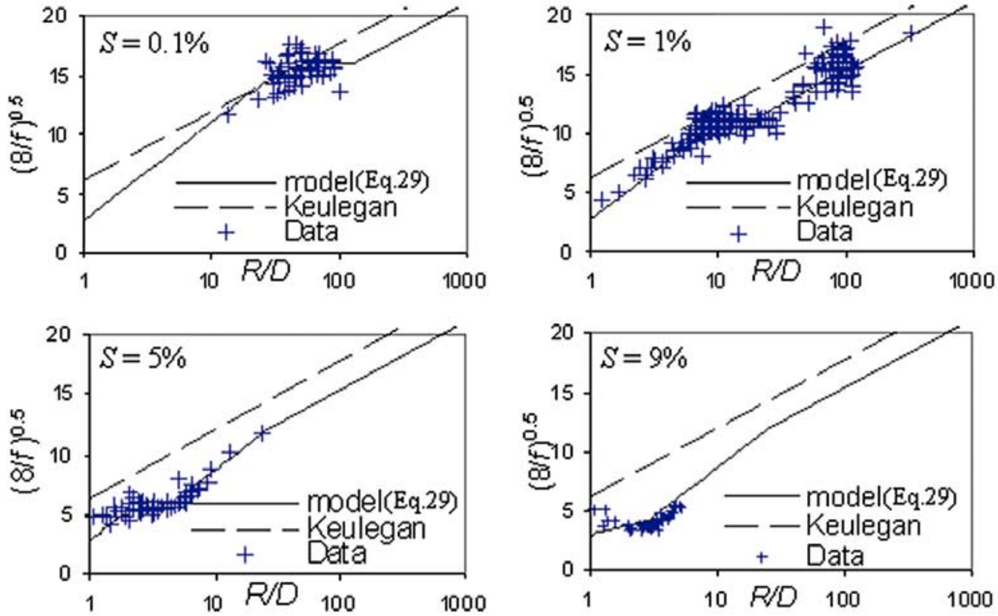

Figure 7. Comparison between the model (equation (29)) and the data obtained with uniform sediments on slopes 0.1, 1, 5, and 9%.

the limits defined for domain 2 (equations (16) and (18)), we could fit the following equation:

$$\alpha_{BR} = 7S^{0.85}\frac{R}{D} \text{ with } 1 < \alpha_{BR} \leq 2.6 \quad (28)$$

Used with Keulegan's equation (equation (2)), it is equivalent to equations (14) and (15) proposed for flows with bed load on a gentle slope (domains 2 and 3).

[46] There is no clear explanation why, according to the data set, α_{BR} attains a maximum at 2.6. Additional analyses not presented here [*Recking*, 2006] indicate that when α_{BR} < 2.6 (domain 2), the bed load layer is discontinuous and of nonuniform thickness, and it evolves with an increasing bed load transport rate until it becomes perfectly continuous and uniform at the transition in domain 3, i.e., when α_{BR} = 2.6. This makes it possible to hypothesize that only the upper part of the bed load layer in contact with the main flow contributes to the development of the wake layer, and that when it becomes uniform for an intense transport rate, the wake zone development is maximum for a given material. However, α_{BR} = 2.6 corresponds to an adjustment of the entire data set, and this value is debatable, especially for a very intense transport rate (sheet flows) for which several authors have proposed a function in the form $k_s \propto \theta D_x$ [*Wilson*, 1987; *Yalin*, 1992; *Sumer et al.*, 1996; *Bayram et al.*, 2003; *Camenen et al.*, 2006].

[47] The roughness layer effects on steep slopes with low relative depth (as was observed on fixed beds) and the roughness layer generated by a bed load layer (as was observed on gentle slopes) are not very different in nature. Flow resistance measured with bed load on steep slopes should integrate both effects. It is difficult to predict how these effects interact, but the entire flow resistance model (equations (2)–(18) and Figure 3) is adequately reproduced with Keulegan's equation (equation (2)) when k_s is defined with the product $\alpha = \alpha_{RL}\alpha_{BR}$ (equation (29)).

$$\sqrt{\frac{8}{f}} = 6.25 + 5.75\log\left(\frac{R}{\alpha_{RL}\alpha_{BR}D}\right) \quad (29)$$

This is illustrated with Figure 7 where equation (29) is compared to the data set obtained on 0.1, 1, 5 and 9% slopes. Using $k_s = \alpha_{RL}(\alpha_{BR}D)$ is equivalent to considering that the steep slope and low relative depth roughness layer effects are applied (through α_{RL}) to a roughness height that is the equivalent roughness $\alpha_{BR}D$ developed by the bed load layer. This equivalent bed roughness function can be seen as a rough integration of the turbulence complexity associated with the gravel bed experiments considered.

[48] The data set indicates that bed load increases flow resistance. But this is only a general trend observed for a wide range of flow conditions that may hide a more complicated pattern for particular flow conditions. For instance, some authors observed that a low bed load transport rate may also cause opposite effects on flow turbulence and mean velocity [*Carbonneau and Bergeron*, 2000; *Nikora and Goring*, 2000; *Campbell et al.*, 2005]. No clear explanations were advanced for this phenomenon. *Campbell et al.* [2005] hypothesized that it resulted from the fixed bed smoothing because of transported fine materials. But, more generally, complex interactions between a low transport rate and a fixed bed roughness layer remain to be investigated.

5.3. Field Implications

[49] A last issue to be discussed is the relevance of this research to natural rivers. The first question concerns the grain diameter. As all models were developed and tested from flume data obtained with uniform material of a single

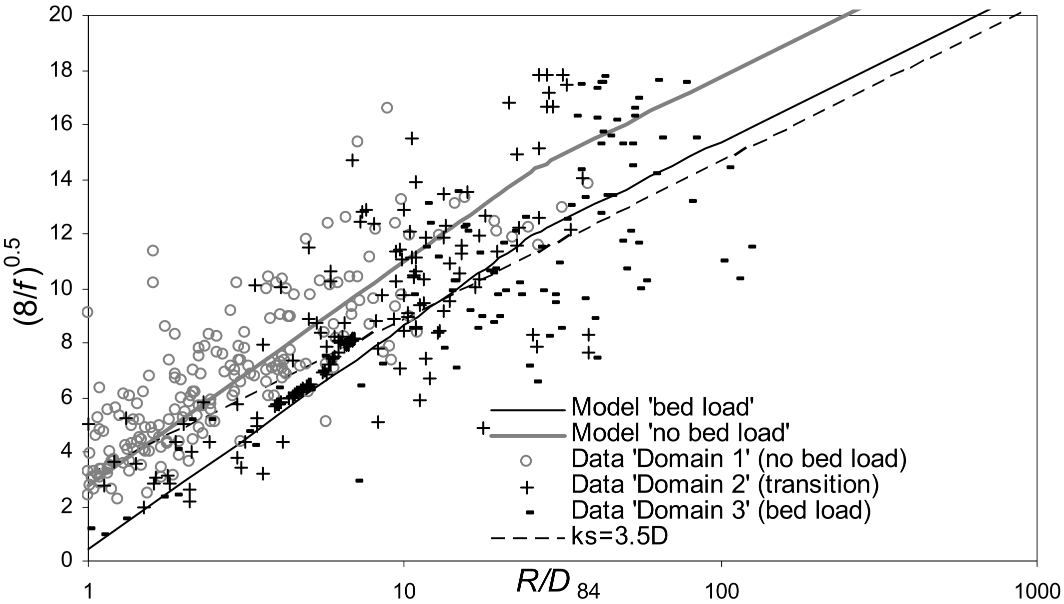

Figure 8. Model comparison with 557 field data (from Table 3 except data from *Limerinos* [1970] as slopes were unknown).

grain size D, which size D_x is the most representative in natural nonuniform sediment? Large diameters such as D_{84} (the size such that 84% is finer) or D_{90} are commonly admitted to be most representative of the bed roughness height for natural gravel bed flows because this percentile is the one that behaves in a widely graded mixture as if it were a well-sorted mixture [*Limerinos*, 1970; *Gomez*, 1993; *Lenzi et al.*, 2006]. This can logically be explained from the discussion above given that in presence of a nonuniform roughness height, the roughness layer development was found to be controlled essentially by larger elements protruding from the bed [*White*, 1940; *Nowell and Church*, 1979], and consequently, large particle diameters would be the best to scale the hydraulic radius in such turbulent flows.

[50] To test the validity of the flow resistance model and the effectiveness of a bed load–flow resistance interaction, the data sets presented in Table 3 were used. As was pointed out by *Ferguson* [2007], this comparison is very difficult because of large uncertainties associated with field measurements. The data set was tested with $D = D_{84}$. For *Hey and Thorne*'s [1986] data, D_{84} was estimated from the mean diameter D_{50} and the sediment standard deviation σ by considering a symmetrical size distribution, as hypothesized by the authors. Since D_{84} was not available for *Griffiths* [1981] and *Samide* [1971] data, we used the approximation $D_{84}/D_{50} \approx 2.2$ by analogy with the available data set. Results are plotted in Figure 8. Data from *Limerinos* [1970] globally fit the model very well, especially for the nontransport zone, but since no slope indications were given by the author, it was not possible to distinguish between flows with and without transport; consequently, this data set was not plotted in Figure 8. The correspondence with the model is globally good, in particular for flows without bed load (domain 1). It was not possible to match the model with D_{50}, confirming that D_{84} is appropriate. More precisely, using *Bathurst et al.* [1981] data, the best fit was obtained with the D_{84} of the intermediate b axis of the clasts, as was also observed by *Limerinos* [1970]. However, no comparison was possible between field data and Keulegan's law (considered here for flows with no bed load and $R/D > 25$) because for high relative depth, all available data were associated with bed load; since the law of the wall should be valid (no wake zone), the mean diameter D_{50} could be the representative grain diameter as was proposed by *Keulegan* [1938], instead of D_{84}.

[51] The scatter is greater for flows with bed load. This is not very surprising since the measurements are very delicate for such high-flow conditions. For instance, although *Pitlick* [1992] measured flat bed to low-relief bed forms (a few grain diameters high), *Griffiths* [1981] did not take direct measurements of the bed deformation during floods. However, in addition, experiments [*Recking*, 2006] also indicated that when sediments are not uniform, domain 2 is associated with a very efficient grain-sorting process, which somewhat complicates the whole phenomenon. One additional source of scatter could be the characteristic grain diameter. Indeed, there are no reasons for D_{84} to be the appropriate diameter for flow resistance when bed load transport is nonzero and this appropriate diameter may also change as the transport rate increases. But one major difficulty was highlighted by *Smart* [1999]: measuring the diameter during flooding. He also pointed out the problems measuring the appropriate energy slope during a flood event, which can be far greater than the mean geometric slope. As a consequence, a rigorous investigation of bed load effects on flow resistance, as was done with uniform sediments in flume data, was not possible, but qualitatively, the correspondence was good with respect to slope. This is particularly well illustrated in Figure 9, where the model fit the field data on slopes 0.00158 and 0.00745 quite adequately, despite all the uncertainties mentioned above. Figure 9 also shows that the model compare fairly well with data obtained by *White and Day* [1982] on slopes 0.001, 0.002 and 0.003 with nonuniform sediments in a 2.42 m wide flume. However, some data (in particular those from *Andrews* [1994] and *Mueller et al.* [2005]) also seem to indicate that when the

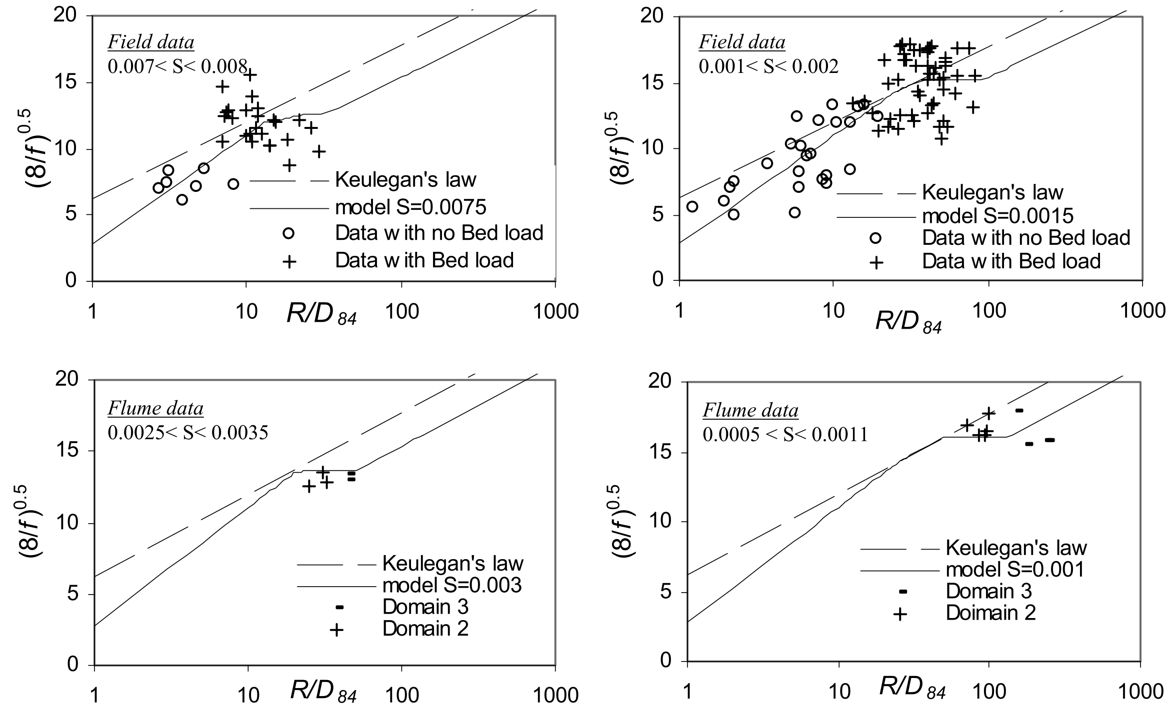

Figure 9. Comparison between the model (equation (29)) and the flume [*White and Day*, 1982] and field data obtained with nonuniform sediments on slopes 0.001, 0.003, and 0.007.

flow transports the finer clasts between immobile D_{84} the transition between the nontransport and transport parts of the model could occur at lower R/D_{84} values than predicted by equation (29). Additional measurements would be necessary to confirm this.

[52] It is common to consider that the Keulegan equation can be used for gravel bed rivers using $k_s = 3.5D_{84}$. This relation is plotted in Figure 8 and it may correspond to the better fitting when a single logarithmic function is used for the entire data set (without distinguishing bed load transport rates).

[53] In poorly sorted gravels, flows can occur for $R/D_{84} < 1$. Since in such conditions the flow could no longer interact with the top of these large grains, the wake effect is expected to be damped and as a consequence a change in the flow resistance is expected. This was checked with the data set restricted to 612 flume and field values obtained without bed load transport: 264 flume data obtained with uniform sediments (Tables 1 and 2), 88 flume data obtained with poorly sorted sediments [*Bathurst et al.*, 1981], and 260 field data (from Table 3). Data are plotted on Figure 10 and confirm this change. Three flow types can be distinguished, as was already observed by *Bathurst* [1985]: the large-scale roughness ($R/D_{84} < 1.4$), the intermediate-scale roughness ($1.4 < R/D_{84} < 25$), and the small-scale roughness ($25 < R/D_{84}$). For large-scale roughness, the data set considered was adequately modeled by setting $1 \leq \alpha_{RL} \leq 3.5$ in equation (27). In these flows, the resistance is partly controlled by the drag exerted by large immobile grains (D_{84}), but a roughness layer may also develop from the flow's interaction with the largest submerged clasts diameter (especially if the large boulders are spaced far apart).

[54] A second problem in extending flume results to field applications was discussed by *Ferguson* [2007] and concerns theoretical limitations of velocity calculations in gravel bed and boulder bed streams. In other words, can a unique depth–velocity relation be used for flow resistance and bed load prediction? The present study has highlighted one of these limitations: the effects of bed load on flow resistance. However, other limitations may also exist. *Ferguson* [2007] suggested the nonuniqueness of mixing length development over a given roughness height. This was illustrated in previous discussions with the development of a turbulent roughness layer that is likely to change with relative depth and slope for a given roughness height and density. However, roughness layer properties are poorly documented and the scaling of the total flow depth with a unique grain diameter such as D_{84} may not be sufficient. A better understanding of parameters controlling the roughness layer development may help to understand how flow resistance equations valuable in flume experiments are still pertinent in the field.

[55] Field bed load prediction should also be discussed. The bed load transport model (equations (21) and (23)) was proposed for uniform sediments, with the same diameter D responsible for both flow resistance (through the roughness layer development) and bed load transport. In the field, both phenomena will more likely be dissociated, with the roughness layer development (and associated flow resistance and mean flow velocity) controlled by D_{84} (as discussed above) and bed load transport associated with smaller diameters. As a consequence, the measured mean flow depth H may quite accurately reproduce the mean flow velocity U when used with D_{84} in equation (29) but may also lead to overprediction if used with a smaller diameter such as D_{50} to compute the Shields stress in the bed load transport model (equations (21) and (23)). This hypothesis is supported by the comparison between the critical Shields relation developed in this study

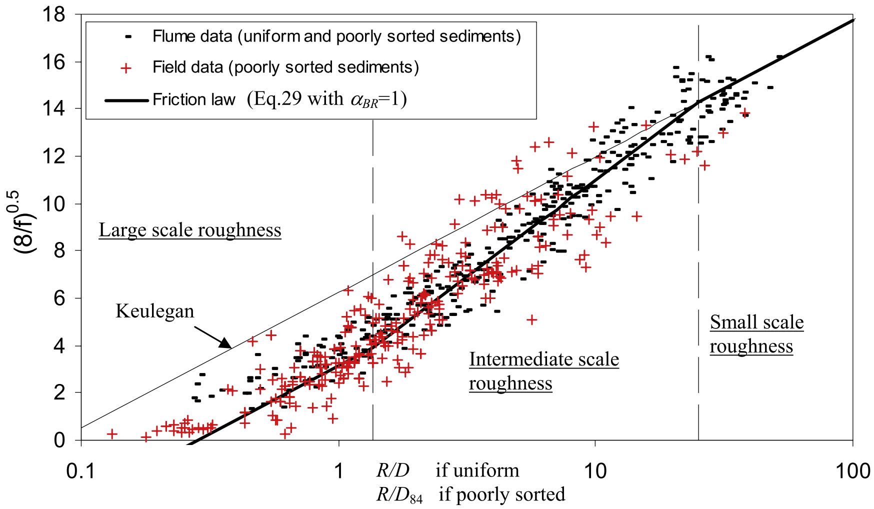

Figure 10. Data set of 612 flows without bed load transport (five outliers were removed): 352 values from flume (values considered in Tables 1 and 2 plus 88 additional data from *Bathurst et al.* [1981]) and 260 from field experiments (Table 3).

considering flows over uniform sediments (equation (22)) and the field relation that *Mueller et al.* [2005] derived from the study of 45 natural gravel beds. To obtain this field relation, the critical shear stress was calculated from the ratio between the measured flow depth H and the median diameter D_{50}. For slopes less than or equal to 1% (i.e., when the wake effects can be ignored) the flume and field functions produce exactly the same critical Shields values. For slopes steeper than 1%, the field relation produces higher values, and the steeper the slope (i.e., the greater the wake effect) the greater the difference. A partitioning method was proposed by *Yager et al.* [2007] to take such effects into account in motionless large grains (as is usually done to take bed form drag into account), but this correction could also be necessary when all grains are in motion so as to take into account drag and lift forces applied to finer grains moving in the low-velocity zone [*Wiberg and Smith*, 1991].

[56] Particular attention must be paid to extreme flow conditions on steep slopes. Models proved to adequately reproduce mean flow velocities and bed load values measured on very steep slopes (over 10%) when calculations were made from the flow discharge, grain diameter and slope. However, in field applications, available data are not flow discharges but more usually flow depth measurements that are related to the flow sediment mixture (whose concentration can be very high on very steep slopes). As a consequence, the equations proposed in this study should be used with caution (see *Smart and Jaeggi* [1983], *Smart* [1983], and *Rickenmann* [1990, 1991] for more details).

6. Conclusion

[57] The purpose of this study was to investigate whether taking into account feedback between flow resistance and bed load would improve bed load prediction. This investigation was conducted by considering a data set of 1567 values obtained in flume experiments over uniform sediment mixtures including available data and the author's measurements. This resulted in the following conclusions:

[58] 1. Feedback effects require distinguishing three flow domains: (1) domain 1 ($\theta < \theta_c$), in which there is no bed load and f decreases with increasing relative depth R/D ($k_s = D$); (2) domain 2 ($\theta_c < \theta < 2.5\theta_c$), in which the bed load layer is not continuous and is not of uniform thickness and the resistance coefficient f is constant for a given slope (which corresponds to a k_s increase from D to $2.6D$); and (3) domain 3 ($\theta > 2.5\theta_c$), in which the bed load layer is continuous and uniform with a thickness several times the grain diameter and f decreases with increasing relative depth R/D ($k_s = 2.6D$).

[59] 2. A new flow resistance equation (equation (29)) was derived. We concluded that although the bed roughness k_s can be set as a constant (as is usually done) in domains 1 and 3 (respectively, $k_s = D$ and $k_s = 2.6D$), a flow-dependent relation should be used in domain 2 (which corresponds to a transition from $k_s = D$ and $2.6D$, and can be approximated by a constant Darcy-Weisbach resistance coefficient f, whatever the value of R/D for a given slope). The new flow resistance model was successfully tested on the entire data set.

[60] Second, the bed load data set was considered with regards to the three domains considered. It was concluded that the distinction between domains 2 and 3 remains relevant for bed load. We were able to dissociate the data set into two groups according to each domain. In domain 2, the data set clearly indicates a slope effect. New coefficients were proposed for the bed load equation based on the tractive force concept, including a slope-dependent critical Shields number relation $\theta_c(S)$ deduced from the flow resistance equations. This new model proved to be more accurate than other existing models, using the Shields numbers θ deduced from the measured mean flow velocities.

[61] For the entire data set, the flow resistance–bed load model was used to calculate bed load, knowing the flow discharge Q, the slope S and the grain diameter D. The scores obtained with the tests indicate that new bed load equations fitted on the data set can reduce the error by a factor of 2 when compared to other existing equations.

[62] The flow resistance model was compared with field data in the discussion. Although the correspondence is qualitatively good, all uncertainties that are associated with field data collection did not permit a clear conclusion, as was possible with flume data.

[63] The wakes that are shed from immobile grains on steep slopes and by grains in movement could explain how the logarithmic flow resistance model departs from the classical Keulegan law established for clear water flows on gentle slopes. Better knowledge of these turbulence properties could help to reduce the scatter observed with field data, but also to understand how equations derived from flume experiments are adequate in field problems.

[64] To conclude, flow resistance and bed load should not be dissociated in model derivation. With additional research, this study should improve field bed load prediction, in cases requiring an estimate of the tractive force from the energy slope and the flow discharge.

Notation

- D uniform sediment diameter.
- D_x sediment grain diameter (subscript denotes percent finer).
- f Darcy-Weisbach resistance coefficient.
- Fr Froude number $Fr = U/(gH)^{1/2}$.
- H flow depth.
- K_s grain resistance Manning-Strickler coefficient $K_s = 21/D^{1/6}$.
- k_s equivalent bed roughness.
- κ von Karman coefficient equal to 0.4.
- Q flow discharge.
- q_b volumetric solid discharge per unit width.
- Q_s sediment discharge for equilibrium flow conditions.
- R hydraulic radius (corrected for sidewall effects).
- Re Reynolds number $Re = UR/\nu$.
- $Re*$ roughness Reynolds number $Re* = u*D/\nu$.
- s relative density of sediment (ρ_s/ρ).
- S energy slope.
- U vertically averaged flow velocity.
- $u*$ shear velocity: $u* = \sqrt{(\tau_o/\rho)}$.
- W flume width.
- α bed roughness to grain diameter ratio k_s/D_x.
- σ sediment geometric standard deviation.
- τ local boundary shear stress $\tau = \rho gRS$.
- θ Shields parameter $= \tau/[(\rho_s - \rho)gD]$.
- θ_c critical Shields value corresponding to grain entrainment.
- θ_l Shields number for the transition from domain 2 to domain 3.
- Φ dimensionless transport rate: $\Phi = q_b/[g(s^{-1})D^3]^{0.5}$.
- ρ density of water.
- ρ_s density of sediments.
- ξ constant of the logarithmic law as derived from the Nikuradse concept.

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