

1 **Assesment of bedload equations using data obtained with tracers in two coarse-bed mountain**  
2 **streams (River Narcea basin, NW Spain)**

3 Daniel Vázquez-Tarrió<sup>\*1</sup> and Rosana Menéndez-Duarte<sup>2</sup>

4 <sup>1</sup> Irstea, UR ETNA, 2 rue de la Papeterie-BP 76, F-38402 St-Martin-d'Hères, France

5 <sup>2</sup> INDUROT (Universidad de Oviedo), Edificio de Investigación, c/Gonzalo Gutiérrez de Quirós, s/n,  
6 Campus de Mieres. 33600, Mieres, Spain

7 **\*Corresponding author:** Tel: +34 984082158; e-mail: [danielvazqueztarrio@gmail.com](mailto:danielvazqueztarrio@gmail.com)

8 **Abstract**

9 Fluvial channels placed in mountain basins show an important decrease in slope when compared with  
10 the immediate upstream torrential reaches, and this fact happens very close to the sediment producing  
11 areas. Consequently, coarse sediment deposits into these reaches. Then, channel bed sediment  
12 typically falls in coarse ranges of grain sizes, being bedload transport very sporadic and occurring with  
13 flow conditions close to the threshold ones. Rivers from NW Spain are defined by this situation,  
14 dropping by 2,000 m in a short path (50 km). In this region, drainage networks with relatively steep  
15 slopes, and where channel bed sediment is typically coarse, develop. Tagged stones were used to trace  
16 bed sediment movement during flood events in River Narcea basin. By this way, bedload transport  
17 rates between 0.2 and 4.0 kg/s were estimated for six flood episodes.

18 After doing that, nine different transport equations were applied. The bedload discharges estimated  
19 with these formulas were compared with the bedload rates obtained with the tracer experiment. None  
20 of the chosen equations performed adequately: all of them tend to overestimate when compared with  
21 the tracer results, being the Wilcock-Crowe (2003) equation the only exception. We think that the  
22 overestimation is related to the particular geomorphology of coarse bed mountain rivers in humid  
23 environments. These equations assume how the channel will carry the entire load which is able to  
24 transport, without taking into account potential limitations in the supply of sediment. But in these  
25 rivers, armoring and structural arrangements in the bed are ubiquitous; these features, together with a  
26 low sediment supply coming from upstream forested reaches, define a supply-limited condition for  
27 these channels limiting the potential use of bedload equations. Wilcock-Crowe (2003) equation  
28 introduces complex corrections into the 'hiding function', and considers the effect of sand content on  
29 entrainment; this could explain why it performs better.

30 **Keywords:** bedload; bedload formulae; fluvial sediment transport; coarse-bed streams; mountain  
31 rivers; sediment transport equations

## 32 1. INTRODUCTION

33 Bedload transport represents an important fraction of the total sediment load carried by the fluvial  
34 system. It controls channel morphology and extension of in-channel habitats (Dufour and Piègay,  
35 2009). Consequently, fluvial research and management requires a good definition of the bedload  
36 dynamics. But estimation of bedload transport rates has been revealed as a very difficult task,  
37 particularly in coarse bed rivers: under natural conditions bedload discharge is not a steady process,  
38 and it shows a strong variability -spatial and temporal (Batalla, 1997; Frostick and Jones, 2002).

39 Numerous sampling devices and field techniques have been developed in order to measure bedload.  
40 Four principal ways of measuring bedload discharge are described in the scientific literature: use of  
41 samplers (Helley and Smith, 1971; Sterling and Church, 2002; Vericat et al., 2006); installation of  
42 sediment traps on the channel (Laronne et al., 1992; Reid et al., 1995; García et al., 2000; Bergman et  
43 al., 2007); the use of tagged clasts as 'bedload tracers' (Haschenburger, 1996; Haschenburger and  
44 Church, 1998; Hassan and Ergenzinger, 2003); and finally, new geophysical and acoustic methods (for  
45 example, Rickenman, 1997; Belleudy and others, 2010; Rennie and Villard, 2004).

46 The proper evaluation of bedload dynamics needs good records of bedload data, but related to the  
47 complexity and time-consuming nature of the methods developed for the study of bedload transport,  
48 obtaining long records of bedload data is expensive. Thus, for many practical purposes bedload  
49 transport is approached by using bedload formulas (López et al., 2013). Several bedload discharge  
50 formulas have been developed during the last decades, based mainly on laboratory data taken in flume  
51 and/or numerical modeling. Few of them were built using field data (Schoklitsch, 1950; Parker et al.,  
52 1982; Bathurst, 2007). The development of these formulae is based on the following premise: a  
53 functional relation should exist between the hydraulic variables, the sedimentological conditions of the  
54 channel and the rates of bedload transport (Gomez and Church, 1989; Batalla, 1997; López et al.,  
55 2013).

56 Evaluating the different equations developed for predicting bedload discharge in gravel bed rivers, and  
57 comparing its predictions with the bedload discharges measured in natural rivers is strongly  
58 interesting. This is the main aim of the current paper, where the authors compare the results obtained  
59 with nine bedload formulas, and the bedload transport rates measured using tracers in two coarse-bed

60 mountain rivers belonging to River Narcea basin (NW Spain). The data of bedload transport rates  
61 measured with tracers were taken from Vázquez-Tarrío and Menéndez-Duarte (2014).

62 Previous attempts in order to evaluate bedload transport equations were made by other authors, but as  
63 Habersack and Laronne (2002) stated, in many cases they were based on data taken in flumes and/or  
64 on field data taken using samplers whose trap efficiencies were in the range of 40-60 % (Carson and  
65 Griffiths, 1987; Gomez and Church, 1989; Chang, 1994; Reid et al., 1996; Batalla, 1997; Bravo-  
66 Espinosa, 2003).

67 Other assessments of transport equations using its own field data were made by García and Sala  
68 (1998), using its own measures in River Tordera with a Birbeck-type sampler (García et al., 1999).  
69 Habersack and Laronne (2002) evaluated several equations using field data taken with a Birbeck trap  
70 in the River Drau (Austria), an alpine tributary from the River Danube catchment. Martin (2003) and  
71 Martin and Ham (2005) evaluated several equations using morphological data in the Vedder river and  
72 the lower Fraser river (Canada), respectively. Recking (2010) made a detailed analysis of the  
73 performance of several bedload equations in mountain sand-gravel rivers, but it is based partially in  
74 flume data. More recently, Lopez et al., (2013) assessed several equations in River Ebro (Spain),  
75 which is a large and strongly regulated river that drains to the Mediterranean Sea.

76 In this work, the performance of these equations is evaluated in two coarse-bed mountain streams  
77 belonging to River Narcea basin (NW Spain). Rivers from NW Spain are typically short and steep  
78 streams. Unlike most of the previous field-based assessments of bedload formulas, climatic conditions  
79 in these rivers are temperate and humid, and upland areas of river catchments are strongly forested.  
80 During the last decades, land use changes and human works (dams, embankments) are  
81 inducing changes in bedload dynamics of these rivers (Fernández et al., 2006; Vázquez-Tarrío  
82 et al., 2012),

83 Despite these, till recent times knowledge about sediment transport in this region was scarce  
84 (Vázquez-Tarrío and Menéndez-Duarte, 2014). In this context, the present work aims not only  
85 to evaluate several bedload equations using field data, but also to increase the comprehension

86 of bedload dynamics in mountain rivers placed in humid and template conditions  
87 (particularly, those fluvial systems draining the Cantabrian Mountain Range).

## 88 **2. REGIONAL SETTING**

### 89 **2.1. Study site**

90 Rivers from NW Spain are characterized by a short path from headwater areas at roughly  
91 2000 m to its regional base level placed in the Bay of Biscay. Climate in the region is  
92 template and humid. Annual average precipitations are around 1100 mm, and they are  
93 uniformly distributed throughout the whole year. Consequently, high gradient and coarse-bed  
94 streams with a regular flow and a pluvial regime typically develop.

95 River Narcea is placed there, in the northern watershed of Cantabrian Mountain Range  
96 (Figure 1A). It has got a catchment surface of 1800 km<sup>2</sup>, which supposes the 9% of the total  
97 surface of the northern watershed of Cantabrian Mountain Range. Bedrock geology of the  
98 basin comprises Paleozoic sedimentary rocks, including limestones, quartzites, sandstones  
99 and shales; in headwater areas some Precambrian metamorphic slates make appearance. This  
100 basement was compressed during the Variscan orogeny, and later it was uplifted in relation to  
101 the Alpine tectonic realm (Álvarez-Marrón et al, 1997).

102 The current regional relief is abrupt, with incised deep river valleys, steeply dipping hillslopes  
103 (average values of slope around 20° and higher), and remaining glacial landforms that are  
104 widely preserved above 1500 m. The highest summits are reached on the southern divide –  
105 around 2200 m. Vegetal cover in the basin is dominated by deciduous forests –mostly beech  
106 and oak forests– in shadow slopes, and bush formations – heather and gorse– in sunny slopes  
107 and elevated areas. Regarding to agricultural and livestock uses, grassland formations are also  
108 common. In general, plant cover is continuous through the whole drainage basin, being only  
109 interrupted in some rocky slopes that are particularly frequent in the most elevated areas of  
110 the basin.

## 111 2.2. Bedload transport rates: previous research

112 In previous works (Vázquez Tarrío, 2013; Vázquez-Tarrío and Menéndez-Duarte, 2014) bedload  
113 transport rates were estimated in two reaches from River Narcea basin using tagged clasts (painted and  
114 with inserted magnets). The two studied reaches were selected in River Pigüeña and River Coto, the  
115 two main tributaries of River Narcea basin (Figure 1B).

116 In River Pigüeña, the study section was chosen on a lateral gravel bar located in the lower part of the  
117 river basin, 1-2 km upstream from the confluence of River Pigüeña with the main channel of River  
118 Narcea (Figure 2A). The surface of the catchment draining to this point is 400 km<sup>2</sup>. Low water  
119 channel has a width of 25 m in this reach, and the bed slope measures 0.007 m/m. The gravel bar  
120 width ranges between 20 and 90 m, and it has got a length of, approximately, 90 m. Surface  $D_{50}$   
121 measures 56 mm, while subsurface sediment is finer; subsurface  $D_{50}$  measures 28 mm. Surface  $D_{50}$  is  
122 then two times coarser than subsurface  $D_{50}$ , suggesting a good degree of armoring. Mean annual  
123 discharge is 4.4 m<sup>3</sup>/s, while the average minimum and maximum annual discharges are 1.1 and 9.5  
124 m<sup>3</sup>/s, respectively. Bankfull discharge is 70 m<sup>3</sup>/s. This discharge corresponds to a flood with a  
125 recurrence interval of 1.5 years.

126 River Coto is placed in a more upstream position in the drainage network than River Pigüeña. In River  
127 Coto, the study section was also chosen on a lateral gravel bar (Figure 2B). Surface of catchment  
128 draining this point is 120 km<sup>2</sup>. Low water channel width measures 15 m in this point, and the bed  
129 slope is 0.01. Surface  $D_{50}$  measures 88 mm and subsurface measures 70 mm. Then, surface  $D_{50}$  is 1.2  
130 times subsurface  $D_{50}$ , suggesting again some degree of bed armoring but less conspicuous than in  
131 River Pigüeña. Bankfull discharge takes a value of 17 m<sup>3</sup>/s; it corresponds to the flow with a  
132 recurrence interval of 1.2 years.

133 In these two gravel bars a total number of 1142 tagged clasts were seeded. During the hydrological  
134 years 2009-2010 and 2010-2011, six flood events with ability to disturb tracer positions were analyzed  
135 –three of them occurring in River Pigüeña and three in River Coto. Table 1 summarizes the main  
136 features of the studied floods (date, time duration, discharge). After these transport events, tracer  
137 displacements were measured along the main longitudinal direction of the channel. Based in Church

138 and Hassan (1992) and Haschenburger and Church (1998), the measured displacements were used to  
139 estimate bedload transport rates.

140 Table 2 collects the bedload transport rates estimated for the studied transport events. Those bedload  
141 rates will be compared further in the text with the results obtained using bedload equations. Also, a  
142 good fit between the measured bedload transport rates and the shear stresses was found. This  
143 regression equation will be used when evaluating the performance of the different bedload equations,  
144 and it follows the next expression:

$$145 \quad q^* = 12,16 \cdot (\tau^* - 0,045)^{4,14} \quad (1)$$

146 In Vázquez-Tarrío and Menéndez-Duarte (2014), all the details about the measurement of the bedload  
147 transport rates and the tracer experiment are widely explained.

### 148 **3. METHODOLOGY**

#### 149 **3.1 Selection and description of the bedload transport formulaes**

150 We selected nine bedload formulas that have been widely used in coarse-bed streams comparable to  
151 those studied here (Martínez Marín, 2001; Wilcock et al., 2009): Du Boys-Straub (Straub, 1935),  
152 Schoklitsch (1934; 1950), Meyer Peter and Müller (1948), Einstein (1950), Bagnold (1980), Parker-  
153 Klingeman-MacLean (Parker et al., 1982), Parker and Klingeman (1982), Parker (1990) and Wilcock  
154 and Crowe (2003).

155 The idea behind the development of those equations is that the intensity of bedload discharge is  
156 functionally related to some hydraulic parameter which quantifies the magnitude of flow discharge; in  
157 general, they are functional relations of the following kind:

$$158 \quad q = c \cdot (x - x_c)^b \quad (2)$$

159 where  $q$  is the bedload transport rate,  $c$  and  $b$  are constant parameters determined empirically, and  $x$  is  
160 the parameter which represents flow discharge: discharge, shear stress or stream power.

161 Following Graf (1971), Gomez and Church (1989) and Habersack and Laronne (2002), the different  
162 equations could be classified in four groups: (i) ‘duBoys type’, based on a shear stress-bedload relation  
163 (DuBoys); (ii) ‘Schoklitsch type’ equations, which are based on a discharge-bedload relation

164 (Schoklitsch, Meyer Peter-Müller); (iii) ‘Einstein type’, which consider relative size effects and  
165 statistical constraints; and (iv) ‘Bagnold type’, based on stream power.

166 In order to facilitate the exposition and the discussion of the results, in this work we have preferred to  
167 classify the different equations in two groups: ‘classical equations’ and ‘modern equations’. ‘Classical  
168 equations’ are those equations which are based on Eq. (2) (Du Boys, Shocklitsch, Meyer Peter-Müller,  
169 Einstein and Bagnold). ‘Modern equations’ are based on the so called ‘similarity collapse’ hypothesis;  
170 they include complex considerations (Parker-Klingeman-MacLean, Parker-Klingeman, Parker and  
171 Wilcock-Crowe) concerning to relative size effects, bed armoring and the influence of sand content.

### 172 3.1.1. ‘Classical equations’

173 Du Boys-Straub (DB-S) represents the first proposed theoretical model for bedload transport (Du  
174 Boys, 1879; Straub, 1935). It is based in the ‘excess shear stress’ concept: the sediment transport will  
175 initiate once the basal shear stress in the channel reaches a threshold value. It was developed to  
176 describe the gravel motion in River Rhone (Gomez and Church, 1989), and it was used later by Straub  
177 (1935) in order to quantify the sediment transport in River Missouri.

178 The DB-S equation has been used in previous works, as for example Shullits and Hill (1968) and  
179 Gomez and Church (1989). Here, Du Boys equation was used following the formulation suggested by  
180 Straub (1935):

$$181 \quad q_b = k \cdot \tau \cdot (\tau - \tau_c) \quad (3)$$

$$182 \quad k = \frac{0,01003}{g \cdot D^{\frac{3}{4}}} \quad (4)$$

$$183 \quad \tau_c = (41,8 \cdot D^{0,82}) - [0,017 \cdot \ln(454 \cdot D)] \quad (5)$$

184 where  $q_b$  is the bedload rate,  $k$  is a coefficient depending on grain size  $D$ ,  $\tau$  is the shear stress and  $\tau_c$   
185 the critical shear stress for entrainment.

186 Schoklitsch (SC) (Schoklitsch, 1950) equation is based in discharge, not in shear stresses. It was built  
187 using experimental data taken at the lab (Gomez and Church, 1989). In this work, it was used this  
188 equation in the form proposed in Schoklitsch (1950):

$$189 \quad q_b = 2500 \cdot S^{\frac{3}{2}} \cdot [Q - 0,6 \cdot (D^{\frac{3}{2}} / S^{\frac{7}{6}})] \quad (6)$$

190 where  $S$  is the channel slope,  $Q$  is the discharge per unit of channel width, and  $D$  the representative  
191 grain size for the bed sediment. It has been used the 40<sup>th</sup> percentile ( $D_{40}$ ) of the grain size distribution  
192 (Gomez and Church, 1989).

193 Meyer Peter and Müller (MP-M) equation (Meyer Peter and Müller, 1948) probably constitutes the  
194 most widely used equation when estimating bedload transport rates in natural rivers (Church and  
195 Hassan, 2005). This equation was built based mainly on experimental data taken at the lab of ETH  
196 (Zurich, Switzerland), and it was initially based in flow discharge (García and Sala, 1998). Chien  
197 (1954) was able to put this equation in terms of the ‘excess shear stress’. Years after, Chien’s (1954)  
198 approach was improved by Wong and Parker (2006). In the current work it was used the Meyer Peter-  
199 Müller formulae in the way suggested by Wong and Parker (2006):

$$200 \quad q^* = 3,93 \cdot (\tau^* - 0.0495)^{1,5} \quad (7)$$

201 where  $q^*$  and  $\tau^*$  are the dimensionless bedload rate and the dimensionless shear stress, which are  
202 defined by means of the Einstein parameter (Einstein, 1950) and the Shields parameter (Shields,  
203 1936), respectively:

$$204 \quad q^* = \frac{q_s}{\sqrt{(s-1) \cdot g \cdot D^3}} \quad (8)$$

$$205 \quad \tau^* = \frac{\tau}{(s-1) \cdot \rho \cdot g \cdot D} \quad (9)$$

206 where  $s$  is the specific weight of solid,  $g$  the acceleration of gravity, and  $\rho$  the density of the sediment.  
207 Einstein (EI) (equation Einstein, 1950) was one of the most complete and complex theoretical  
208 approaches to sediment transport (Graf, 1971; Gyr and Hoyer, 2006). It is a probabilistic model based  
209 in the stochastic nature of sediment entrainment. With his probabilistic approach, Einstein aimed to  
210 take into consideration the effects of the turbulence, and the effects of particle location in the bed (Gyr  
211 and Hoyer, 2006). The practical application of Einstein (1950) model to real cases was very  
212 complicated (Gomez and Church, 1989; Martínez Marín, 2001), but Parker (1979) proposed an  
213 experimental fit based in shear stress. The latter is the approach followed in the current research:

$$214 \quad q^* = 11,2 \cdot (\tau^*)^{1,5} \cdot \left(1 - \frac{0.03}{\tau^*}\right)^{4,5} \quad (10)$$

215 Bagnold (BA) equation (Bagnold, 1980) is based in the stream power, which Ralph Bagnold  
216 considered a useful parameter when quantifying the geomorphological work made by rivers on the  
217 landscape. The BA equation follows the next mathematical expression:

$$218 \quad q_b = \frac{s}{s-1} \cdot 0.01 \cdot \left[ \frac{\omega - \omega_0}{0.5} \right]^{3/2} \cdot (Y/0.1)^{-2/3} \cdot (D/0.0011)^{-1/2} \quad (11)$$

219 where  $s$  is the specific weight of the bed sediment,  $\omega$  the stream power and  $\omega_0$  the critical stream  
220 power. Stream power is estimated using the following function:

$$221 \quad \omega = \frac{Q \cdot S \cdot \rho \cdot g}{B} \quad (12)$$

222 where  $B$  is the channel width and  $S$  the channel slope.

223 When computing  $\omega_0$ , Ferguson (2005) introduced several corrections to Bagnold's (1980) formula. In  
224 this paper, computations were based in the Bagnold's equation as suggested by Ferguson (2005):

$$225 \quad \omega_0 = 2860 \cdot (D_{50})^{1.5} \cdot \log\left(0,235 \cdot \frac{D_{50}}{D_{90} \cdot S}\right) \quad (13)$$

226 where  $D_{50}$  and  $D_{90}$  are the 50<sup>th</sup> and 90<sup>th</sup> percentile of the grain size distribution.

### 227 3.1.2. 'Modern equations'

228 The different equations classified here as 'modern equations' share a common background. Firstly, all  
229 of them are based in the 'similarity collapse' hypothesis (Parker and Klingeman, 1982): according to  
230 this hypothesis, the shape of the functional relation between shear stress and bedload discharge is not  
231 dependent on grain size (Parker and Klingeman, 1982; Wilcock et al., 2009). Secondly, these  
232 equations also consider that 'critical shear stress' (the shear stress needed for entrainment) should vary  
233 with the grain size following an exponential function called the 'hiding function' (Parker and  
234 Klingeman, 1982; Parker, 2008; Wilcock et al., 2009).

235 Despite these general considerations, each one of the modern equations has its own particularities. For  
236 example Parker, Klingeman and MacLean (P-K-MC) equation (Parker et al., 1982) was developed  
237 using field data taken in Oak Creek (Oregon, USA) and Elbowe River (Canada), and it is based in the  
238 50<sup>th</sup> percentile ( $D_{50}$ ) of the subsurface grain size distribution. Parker and Klingeman (P-K) equation

239 (Parker and Klingeman, 1982) is similar to P-K-MC, but it firstly calculates fractional transport rates  
240 for each size class, and then summarizes for the whole sediment mixture.

241 Parker (P) equation (Parker, 1990) was also based in the bedload discharge data from Oak Creek. It  
242 was developed from P-K-MC, but it uses the surface grain size distribution in its computations. This  
243 equation excludes sand sediment assuming that during the transport events with ability to displace  
244 gravel sediment, the sand should be carried as suspension load (Wilcock et al., 2009).

245 Finally, Wilcock and Crowe (W-C) model (Wilcock and Crowe, 2003) was developed based in  
246 experiments carried out in flumes with mixed sand-gravel sediment. Sand is explicitly considered in  
247 this model based in Wilcock et al., (2001), who observed how in recirculating flumes sand sediment  
248 increases gravel mobility.

### 249 **3.2 Performance, comparison and evaluation of bedload formulas**

250 In this work the different bedload equations were performed following different procedures. Firstly,  
251 they were calculated the bedload discharges corresponding to each one of the flood events described in  
252 section 2.2, and studied with tracers. Using the hydraulic parameters (discharge, shear stress)  
253 corresponding to each one of those flood events (Table 1), the bedload discharges were computed  
254 using the different equations. In the case of ‘modern equations’, the calculus was accomplished using  
255 BAGS, a PC-based software developed to compute bed load transport in gravel-bed streams (Pitlick et  
256 al., 2009; Wilcock et al., 2009).

257 After carrying out the flood event-computation, it was constructed the bedload rating curve for each  
258 equation. The bedload rating curves plot bedload transport rates as a function of shear stress.

259 DB-S, MP-M and EI equations are based in the shear stress; then, these curves were built directly  
260 assigning values to shear stress in the equations. With modern equations it was used the bedload rating  
261 curve built with BAGS. BAGS uses in its computations an algorithm based in the Keulegan’s  
262 resistance formulae and the Manning-Strickler equation (Pitlick et al., 2009; Wilcock et al., 2009).  
263 Furthermore, BAGS algorithms work with the partition between grain and form resistance when  
264 computing bed shear stress, using the following formula which is derived from the Manning-Strickler  
265 equation:

266  $\tau' = 17 \cdot (S \cdot D_{65})^{1/4} \cdot U^{3/2}$  (14)

267 where U is the flow velocity; it is calculated using the Keulegan resistance formula:

268  $\frac{U}{\sqrt{g \cdot R \cdot S}} = 2,5 \cdot \ln\left(11 \cdot \frac{R}{k_s}\right)$  (15)

269 where R is the hydraulic radius, and  $k_s$  the equivalent roughness that was calculated as two times the  
270 65<sup>th</sup> percentile of the grain size distribution ( $2D_{65}$ ).

271 The shear stress calculated using Eq. (14) is used by BAGS when performing P-K-MC, P-K, P and  
272 W-C equations.

273 Finally, SC and BA equations are based in the discharge (stream power could be calculated from the  
274 discharge). We use the topographical channel section built with Total Station in order to compute the  
275 relation between hydraulic radius, and the wet surface of the channel cross-section. Then, using  
276 Keulegan equation it was computed the relation between hydraulic radius and the mean flow velocity.  
277 Finally, based in the hydraulic radius-slope product for shear stress, and the wet surface-flow velocity  
278 product for discharge, it was constructed the relation between shear stress and discharge for the two  
279 studied streams. After that, it was possible to build the bedload rating curve.

280 Then, the bedload discharges computed with the different equations were compared with the bedload  
281 rates obtained with the tracer experiment. By this way, we proceeded to evaluate the bedload formulas.  
282 The comparison was made in two different ways:

283 - By means of a “discrepancy index’ ( $r$ ), which could be defined as the ratio between the  
284 calculated (with equation) and the observed (with tracers) bedload rates.

285 That index is similar to the one used by Batalla (1997) or Habersack and Laronne (2002) in  
286 their assessment of bedload transport equations. Following Habersack and Laronne (2002), it  
287 was also computed the geometric mean of those indexes, using the following expression:

288  $\hat{r} = (r_1 \cdot r_2 \cdot \dots \cdot r_n)^{1/n}$  (16)

289 where  $n$  is the number of data.

290 - By comparing the bedload rating curve built using Eq. (1) with the rating curve built for each  
291 equation.

#### 292 4. RESULTS

293 In tables 3 and 4 they are summarized the results obtained with each equation, and also the  
294 discrepancy indexes obtained when comparing the bedload rates calculated with each equation with  
295 those bedload rates obtained through the tracer experiment. Bedload rates estimated with the equations  
296 are, in general, higher than the bedload rates measured with tracers. The bigger discrepancies are  
297 obtained in River Coto, but in R iver Pig ue a differences are also important; particularly, when  
298 performing the classical equations.

299 The same statistical indexes applied for the set of formulae, were obtained for Eq. (1) too, and they are  
300 also included in tables 3 and 4. This equation represents a regression fit derived from our own data in  
301 the study reach, and then it is not comparable with the rest of formulae. Despite this, those indexes  
302 were calculated in order to facilitate the comparison between the equations and the bedload rates  
303 determined with the tracer experiment.

304 Figure 3 shows the comparison between the bedload rates estimated with the different equations, and  
305 the bedload rates obtained with tracers. Only the 4% of our estimations are in range of 2 of the tracer  
306 measures, and only the 13% are in a range of 10. P-K-MC represents the equation which provides  
307 better results for River Coto, while W-C is the equation which provided the better results for River  
308 Pig ue a.

309 DB-S equation is the one with a higher discrepancy index (close to 20000 in River Coto). SC, MP-M  
310 and EI discrepancy indexes are also high. In River Pig ue a, bedload rates obtained with P-K, P and  
311 W-C are closer to the bedload rates obtained with tracers, being the discrepancy index lower for the  
312 January and June (2010) transport events. In the case of W-C equation, discrepancy index is close to 1  
313 for these two transport episodes; that means, bedload rates estimated with the W-C equation and rates  
314 measured with tracers are almost the same. In River Coto, discrepancy indexes are high, even with the  
315 modern equations: the lowest discrepancy index (12.5) was obtained with B equation.

316 In Figure 4 and 5 the rating curves built with each equation are compared with the rating curves  
317 derived from Eq. (1), for River Pig ue a and River Coto respectively. Several equations overestimate  
318 or overpredict bedload rates for all the range of shear stresses: DB-S, EI, BA and P. In the case of P  
319 equation in River Pig ue a, both curves are very close at shear stresses around 50-70 Pa, which

320 correspond to frequent floods. On the other hand, SC, MP-M and P-K-M equations underestimate  
321 bedload rates with low shear stresses, and strongly overestimate with moderate and high shear stresses.  
322 Finally, in the case of W-C equation both rating curves are very close in River Pigüeña, while in River  
323 Coto the W-C curve strongly differs from the experimental rating curve.

## 324 **5. DISCUSSION**

325 When comparing the bedload discharges computed using the bedload equations, and the bedload  
326 transport rates measured with tracers it is always showed the same trend: overestimation of bedload  
327 transport rates with the equations, with the only exception of W-C equations in River Pigüeña.

328 Our results show how the results given by the different equations are far from those obtained with  
329 tracers. Moreover, the results strongly differ when comparing the different equations one with each  
330 other. 'Classical equations' give bedload discharges which are strongly higher than the bedload rates  
331 obtained with tracers. On the other hand, the 'modern equations' give results closer to the transport  
332 rates obtained with tracers, while they are still higher.

333 In principle, we could interpret these discrepancies in two opposite ways. On the one hand, we could  
334 attribute the discrepancies to the lack of reliability in the estimations made by the equations. On the  
335 other hand, the discrepancies could be attributed to inaccuracies or uncertainties in the measurement of  
336 the bedload rates with the tracer experiment.

337 The bedload rates measured with the tracer experiment described in Vázquez-Tarrío and Menéndez-  
338 Duarte (2014) are in the same order of magnitude as those bedload rates obtained in comparable  
339 coarse-bed streams from other regions of the world (Haschenburger and Church, 1998; D'Agostino and  
340 Lenzi, 1999; Batalla et al., 2005a, b). Instead, the bedload discharges reported by the equations are two  
341 or three orders in magnitude higher than those bedload rates obtained with tracers, and at the same  
342 time they show important discrepancies between them. Then, while it is true that some uncertainty in  
343 the exact value of the bedload rates is unavoidable, we think that the main source of the discrepancy  
344 lies in the inaccuracy of the estimates made with the bedload equations.

345 With the results obtained here, DB-S equation does not seem to be useful for the studied channels.  
346 According to Gomez and Church (1989) and Martínez Marín (2001), that equation was developed  
347 using finer sizes, and it is based in a very simplistic model of sediment transport based in the sliding of

348 several layers of sediment within the river bed. These conditions could not be assumable in coarse bed  
349 streams as those studied here.

350 In some works, good results have been reported for the SC equation (García and Sala, 1998;  
351 D'Agostini and Lenzi, 1999). However, in the current research it does not seem to provide good  
352 estimations. The same could be said about MP-M equation.

353 EI equation shows similar behavior to the previous formulas. This equation was developed based in  
354 flume data taken with sediment finer than the studied channel, and that fact should be taken into  
355 account. Probably, the grain size of the bed sediment in the studied reaches is very coarse in order to  
356 apply EI equation.

357 Regarding BA equation, previous authors have found that this equation, as well as other mathematical  
358 models founded on the stream power concept, do better predictions of bedload transport rates (Gomez  
359 and Church, 1989; Martin and Church, 2000; Martin, 2003). Nevertheless, the differences between  
360 bedload discharges computed in this work using BA equation, and the bedload transport rates  
361 measured with tracers are still important. So, despite BA equation provides better estimations than the  
362 other 'classical equations', it did not give us results good enough.

363 In general, the 'modern equations' do better estimations. The rating curve built using P-K-M equation  
364 underestimated bedload transport rates at low shear stresses. In this sense, it should be taken into  
365 account that this model was developed to be used for shear stress with ability to break bed armoring,  
366 when bed sediment reaches equal mobility conditions (Wilcock et al., 2009). This fact could explain  
367 the underestimation of bedload rates at low shear stresses.

368 Parker equation also showed lower discrepancies in River Pigüeña, but not in River Coto. When  
369 developing this equation, Parker (1990) did not consider the sand sediment content. This could explain  
370 the discrepancies observed here, because sand sediment plays an important role in bedload transport in  
371 coarse bed rivers. Finally, W-C gives very good results in River Pigüeña, but not in River Coto, where  
372 it still overestimated the bedload rates by one order of magnitude. In summary, 'modern equations'  
373 giver better results, being the W-C equation in River Pigüeña the one who provided the best  
374 estimations.

375 Discrepancies between the estimates made with bedload equations, and the real measurements of  
376 bedload rates (using either field as flume data) were also found by other authors. Gomez and Church  
377 (1989) in an analysis made over 12 bedload equations developed for gravel bed river found that any  
378 equation was able to do general predictions of bedload transport rates. They found how the equations  
379 based in stream power gave better results when there is no enough hydraulic data available, and how  
380 EI and P equations provided better results with good hydraulic data.

381 Batalla (1997) observed how MP-M and Ackers-White equations provided better results in a mountain  
382 mixed sand-gravel river placed in Costero-Catalan Range. Also, Reid et al (1996) found that MP-M  
383 equations gives better results than BA and P in an ephemeral gravel bed stream from Israel (Nahal  
384 Yatir). According to García and Sala (1998), in the latter case the river has not a surface armoring,  
385 then the sediment availability was not conditioned by armoring and sediment mobility was only  
386 controlled by the stream capacity. Then, García and Sala (1998) observed how with bed armoring, P-  
387 K-M is the equation which provided better results using its own data obtained in River Tordera.

388 Hoey and Sutherland (1991) evaluated BA equation and found that in equilibrium or aggrading rivers,  
389 this equation overestimated bedload rates; otherwise, in degrading channels this equation  
390 underestimated bedload rates. Nevertheless, in the channels studied here there are no evidences of  
391 aggradation and the equations still overestimate.

392 Martin and Ham (2005) evaluated several bedload formulas using field evidence and a morphological  
393 approach in the Vedder river, and they found that any particular equations is consistently preferred.

394 Rascher et al. (2012) assessed 16 equations in a mountain river placed in Bavaria, using bedload rates  
395 measured with a Helley-Smith sampler. They found how, in general, the bedload equations  
396 overestimated bedload rates. In some cases they obtained values 100 times higher than the measured  
397 bedload rates. Furthermore, they observed how some of the evaluated equations overestimate during  
398 moderate to high flow, while underestimate during low flows. This is similar to what Recking (2010)  
399 found using field and flume data.

400 More recently, López et al. (2013) evaluated various bedload equations using data obtained from  
401 flushing floods studied during 2003 and 2004 in the River Ebro, a large regulated river from the

402 Mediterranean watershed of Spain. They found in many cases discrepancies indexes of 2 to 10  
403 between bedload equations and measured rates.

404 When compared our results with the estimations made by these previous authors, our average  
405 percentage of bedload estimations not exceeding in a range of 2, 5 and 10 the observed rates are in  
406 general lower (Table 5). However, our results are very close to those obtained by Rascher et al.  
407 (2012) in a comparable alpine stream. We think that our low percentages are partially related to the  
408 fact that some of the 'classical' equations (DB-S, SC, EI, BA) evaluated here were not assessed by the  
409 previously cited authors. In fact, when we do not consider those 'classical' equations, our percentage  
410 of 'agreement' increases; the same happens with Rascher et al. (2012) results (Table 5). Despite this,  
411 results from Rascher et al. (2012), and our results, are still low. We think it could be related in some  
412 way to the particular conditions of the rivers studied by Rascher et al. (2012) and us: mountain rivers,  
413 with steep slopes, very coarse beds, and a regular flow discharge along the whole hydrological river.

414 Recking et al. (2012) outlined the following facts in relation to the applicability of theoretical  
415 equations when used to estimate bedload transport rates in coarse-bed rivers: 1) There is no theoretical  
416 model with ability to make general predictions of bedload transport rates in gravel-bed streams  
417 (Gomez and Church, 1989); indeed, theoretical models are only acceptable in the short range of  
418 conditions for what they were defined. 2) During low to medium intensity flow conditions, equations  
419 show the worst results (Barry et al., 2004; Rascher et al., 2012). 3) In coarse bed rivers, errors could  
420 attain several orders of magnitude (García and Sala, 1998; Barry et al., 2004; Bathurst, 2007; Rascher  
421 et al.2012). Furthermore, different authors got different conclusions because the range of data used by  
422 every author was different (Recking et al., 2012).

423 We think that the previous three observations are applicable to our data. We did not find any model  
424 with ability to do satisfactory predictions of bedload rates. We think that there are three main reasons  
425 which could explain the strong overestimation found here: 1) We performed these equations averaging  
426 the flow conditions for the whole channel section and the whole duration of the transport episode,  
427 which involves assuming steady and uniform flow conditions; 2) Limitations in the definition of the  
428 parameters requested by the equations; and 3) Limitations inherent to the equations.

429 Firstly, in relation to point (1), Gomez and Church (1989), based in De Vries (1973) and Csoma  
430 (1973), found that a realistic comparison between measured bedload rates, and estimates obtained  
431 using bedload equations, could be made if it were compared with the measurement of an average  
432 bedload rate which absorbs all the uncertainties linked to short-term fluctuations. That would be  
433 possible if the number of samples, and the time interval of sampling are large enough to cover all the  
434 range of fluctuations (both temporal and spatial) in transport rates.

435 We think that the use of tracers satisfy these requirements. Instantaneous velocities or local rates are  
436 not measured with tagged clasts. Rather than this, this technique allows us to determine average  
437 velocities of bedload (the virtual velocity of Hassan et al., 1992), and based in data obtained with  
438 tracers dispersed across a wide surface of the channel section. In this sense, the observed transport  
439 rates are averaging bedload transport during the whole transport episode and across the whole width of  
440 the channel section. Following Gomez and Church (1989), we could consider that tracers are masking  
441 the effect caused by the fluctuations and unsteady behavior of bedload transport, allowing us to  
442 obtained average bedload rates. Thus, we think that the main discrepancy found in this work is not  
443 related to point (1).

444 Right after, in relation to point (2), Recking et al., (2012) outlined several sources of uncertainty when  
445 applying the bedload equations: slope should be energy slope and not average bed slope (Meirovich et  
446 al., 1998); discharge should be measured locally, not using average values; and finally, grain size  
447 distribution should be properly measured.

448 According to these authors, all these facts result in the accuracy dependence on the time interval  
449 considered when performing the equations: when bedload equations are used to estimate bedload rates  
450 for very short time-scales (instantaneous bedload rates), uncertainty is huge; however, that uncertainty  
451 decreases when the equations are used to calculate sediment transferences at longer time-scales (for  
452 example, annual loads). They linked this to the fact that, at longer time scales, temporal fluctuations in  
453 the different parameters (slope, discharge, grain size) are averaged.

454 Then, following what was pointed out in the previous paragrepahs, we could consider that tracers  
455 averaged the temporal and spatial fluctuations occurred during the transport episode, at least partially.  
456 Furthermore, as Habersack and Laronne (2002) stated, although the formulas theoretically require

457 local rather than average cross-sectional hydraulic data (Gomez and Church 1989), for the derivation  
458 the originators of the equations used average cross-sectional data, straightforwardly available in  
459 practical situations.

460 On the other hand, when talking about the representative grain size introduced in the equations, Bravo  
461 Espinosa et al., (2003) argued that transport conditions vary between the different grain-sizes. Thus,  
462 they stated that estimate bedload transport rates using a unique grain size to represent the whole bed  
463 sediment mixture is not suitable. These authors defined three transport conditions for the different  
464 grain sizes of the bed sediment: those grain sizes that show supply limited transport; those that show  
465 capacity-limited transport; and finally, those grain sizes that show partial capacity-limited transport.  
466 Then, they observed how some equations seem to be more appropriate for each transport condition.  
467 For example, they observed how in capacity-limited conditions, P-K-MC (1982) equation shows better  
468 results. This fact could be contributing in some way to the discrepancies observed here.

469 Finally, in relation to point (3), it should be highlighted that using bedload equations in order to  
470 predict bedload rates involves assuming at least two tacital premises. Firstly, the application of a  
471 bedload formula implies assuming that during the transport event, not only flow conditions, but also  
472 bed material and bedload sediment remain without changes: equations describe bedload as a steady  
473 process (Batalla, 1997). On the other hand, bedload formulas assume 'capacity-limited' conditions:  
474 they compute the maximum load that the river channel is able to carry, and they do not take into  
475 account possible limitations in sediment supply, that are common in natural systems (Wilcock et al.,  
476 2009).

477 The first assumption (steady bedload transport) is not realistic when talking about natural rivers. Not  
478 only because of the spatial and temporal fluctuations in flow conditions, but also in relation to the way  
479 through bedload transport actually takes place. At event scale, bedload transport shows pulses  
480 (Gomez, 1991; Frostick and Jones, 2002) linked to the migration of bedforms and clusters of particles.  
481 Also, transference of clasts from bed material to bed load follows a stochastic behavior (Kirchner et  
482 al., 1990). Moreover, at a particular moment during a transport episode, not all the water discharge is  
483 available for the transport (Gomez and Church, 1989). Furthermore, not all the bed surface is being  
484 involved in the active transport at every moment during the course of a transport episode; rather than

485 this, in every moment different portions of the bed could be activated or inactivated, in relation to the  
486 evolution experienced by the texture of the bed, the structural arrangements and the grain size of the  
487 bed load. All these facts impose a chaotic and non-linear nature to the bedload dynamics at event  
488 scale, which seems very difficult to be considered or included into a deterministic single equation.

489 In relation to the capacity-limited transport assumption, we think that this is the main reason of the  
490 discrepancies found in the current research. We consider that bedload equations estimate not real  
491 bedload rates, but transport capacity (Bravo-Espinosa et al., 2003; Wilcock et al., 2009).

492 However, in coarse-bed rivers transport capacity could not be attained if there is no enough  
493 availability of sediment in the channel (Hicks and Gomez, 2003; Yager et al., 2007; Yager et al.,  
494 2012). A wide variety of intrinsic (bed resistance linked to bed texture and bed forms, bank resistance  
495 to erosion and/or bed armoring) and extrinsic (runoff efficiency and magnitude of erosive processes at  
496 the whole catchment scale) elements of the channel could combine and limit the sediment supply to  
497 the channel.

498 Coarse-bed mountain rivers with perennial flow regimes are featured by the development of bed  
499 armoring and packing. Moreover, structural arrangements and several kind of bed forms (imbrications,  
500 patches, clusters) are not uncommon (Wittenberg and Newson, 2005; Venditti et al., 2008). All of  
501 these structural and textural features locally increase hydraulic roughness and bed resistance,  
502 increasing the threshold stresses for incipient motion (Bathurst, 2007; Yager et al., 2012). These facts  
503 could strongly limit the availability of in-channel sources of sediment (Yager et al., 2007; Recking,  
504 2012).

505 Furthermore, in forested basins the upstream supply of sediment coming from debris flow and  
506 hillslope processes in headwater areas is irregular and sporadic, and this fact could also contribute to  
507 the lack of sediment in the channels (Dietrich et al., 1989; Yager et al., 2007). Particularly, in rivers  
508 draining the Cantabrian mountain range it has been described a slow degrading trend related to land  
509 use changes during the last century (loss of cropping areas, forestation of upland basins), which could  
510 limit the supply of sediment to the high-order channels (Fernández et al., 2006; Fernández and  
511 Anadón, 2010; Vázquez-Tarrío and Menéndez-Duarte, 2014).

512 The previous considerations (low sediment availability, unsteady and non-uniform nature of bedload  
513 transport) could explain why the bedload formulas fail when estimating bedload discharge in the  
514 studied rivers.

515 The ‘modern equations’, like Wilcock-Crowe or Parker-Klingeman-MacLean, are based in well-  
516 defined experimental data taken in coarse bed channels (field and/or flume data). They introduce  
517 complex formulations which take into consideration the bed armoring and its break-up during the  
518 transport episodes (Recking et al., 2012). They also take into account the effect of sand content in the  
519 sediment mixture (Wilcock, 1993; Wilcock and Crowe, 2003), and they make use of hiding functions  
520 in order to catch the dependence of bedload rates on grain size (Parker and Klingeman, 1982; Parker et  
521 al., 1982; Parker, 1990, 2008; Wilcock and Crowe, 2003; Wilcock et al., 2009). Thus, this explains  
522 why those equations provide better results than the ‘classic’ ones.

523 Nonetheless, these equations still do not match the measured bedload rates. In the current research,  
524 with the only exception of the Wilcock-Crowe model in River Pigüena, the rest of tested equations  
525 showed discrepancies ratios higher than 4 or 10. Other authors (López et al., 2013) also found  
526 discrepancies with these modern equations.

527 It seems as this ‘modern equations’ are not picking in its formulation all the features governing  
528 bedload transport in coarse bed rivers. Perhaps, it could happen that some of the tacital assumptions  
529 implicit to the ‘similarity collapse hypothesis’ are only approximated. The ‘similarity collapse  
530 hypothesis’ states that effects of grain size in entrainment are only related to the relative position of  
531 each particle in relation to its neighbors. This assumption is gathered in the form of ‘hiding functions’,  
532 involving that grain size only influences in the scale, but not in the shape of the bedload functions  
533 (Parker, 2008; Wilcock et al., 2009).

534 However, it could happen that other phenomena, apart from relative size effects, could be influencing  
535 clast entrainment. In that sense, Kirchner et al. (1990) pointed out the following: more important than  
536 single shear stresses for each grain size, it would be more correct using distributions of entrainment  
537 probabilities for each grain size, if we aimed to properly consider all the phenomena linked to  
538 fluctuations in turbulence and instantaneous shear stresses; this statement made by Kirchner et al.  
539 (1990) is not considered in the equations tested in the current paper.

540 Then, even the ‘modern equations’ require of some assumptions. In common to the classic equations,  
541 the ‘modern’ formulas are still empirical correlations; of course, more complex than the classical ones,  
542 and scaled by the flow and fitted to different bed conditions.

543 Summarizing, we think that the use of bedload equations for predicting bedload rates needs of  
544 equilibrium channels, availability of in-channel sources of sediment and a well-defined channel  
545 geometry and bed texture. Far from this situation, strong discrepancies between real rates and  
546 predicted ones are expectable.

## 547 **6. CONCLUSIONS**

548 In this work, we tested nine bedload discharge equations using bedload transport rates obtained with  
549 tracers during six flood episodes occurred in River Pigüeña and River Coto, two mountain coarse bed  
550 streams placed in NW Iberian Peninsula.

551 With the only exception of W-C equation in River Pigüeña, none of the assessed equations provided  
552 good estimations. All of them overestimated the bedload transport rates; in the case of the classical  
553 equations, they overestimated in a range of 2 or even 3 orders of magnitude.

554 We think that the origin of these overestimations lies in the particular geomorphological conditions of  
555 mountain coarse bed streams in humid conditions: the occurrence of bed armoring and structural  
556 arrangements in the bed, together with a low upstream sediment supply (linked to the forested  
557 condition of upland basin areas), determine a supply-limited sediment regime which makes not  
558 applicable the tested equations.

559 **Acknowledgements:** The present work has been possible thanks to the financial support  
560 given by the grant AP2007-3209, cofounded by the Spain Minister of Science and the  
561 European Social Funds; and more recently, also thanks to the financial support provided by  
562 the grant ACA14-30, cofounded by the Postdoctoral ‘Clarín’ Program-FICYT (Government  
563 of the Principality of Asturias) and the Marie Curie Cofund. Special thanks should be done to  
564 Raul Lopez and Ramón Batalla, for the important information provided to us. Also, we could  
565 not forget José Crespo and Miguel Fernández for their invaluable help during the fieldwork.

## 566 **7. REFERENCES**

567 Álvarez-Marrón, J., Rubio, E. and Torné, M. 1997. Subduction-related structures in the North Iberian  
568 Margin. *Journal of Geophysical Research*. 102 (B10), 22497-22511.

569 Bagnold, R. A. (1980). An empirical correlation of bedload transport rates in flumes and natural rivers.  
570 *Proceedings of the Royal Society, London, Serie A*. 372, 453-473.

571 Barry, J. J., Buffington, J. M. and King, J. G., 2004. A general power equation for predicting bedload  
572 transport rates in gravel bed rivers. *Water Resources Research*. 40, 10401-10423.

573 Batalla, R. J., 1997. Evaluating bed-material transport equations using field measurements in a sandy  
574 gravel-bed stream: Arbúcies river, NE Spain. *Earth Surface Processes and Landforms*. 22, 121-130.

575 Batalla, R. J., García, C. and Balasch, A., 2005a. Total sediment load in a Mediterranean mountain  
576 catchment (the Ribera Salada River, Catalan Pre-Pyrenees, NE Spain). *Zeitschrift für*  
577 *Geomorphologie*. 49 (4), 495-514.

578 Batalla, R. J., García, C. and Rovira, A., 2005b. A decade of sediment transport measurements in a  
579 large Mediterranean river (the Tordera, Catalan Ranges, NE Spain). In: García, C. y Batalla, R. J.  
580 (eds.). *Catchment dynamics and river processes: Mediterranean and other climate regions*. Elsevier,  
581 Amsterdam, pp. 117-140.

582 Bathurst, J. C., 2007. Effects of coarse surface layer on bed-load transport. *Journal of Hydraulic*  
583 *Engineering*. 133 (11), 1192-1205.

584 Belleudy, P.; Valeté, A. and Graff, B., 2010. Passive hydrophone monitoring of bedload in River  
585 Beds: First trials of signal spectral analyses. *US Geological Survey Scientific Investigations Report*  
586 2010-5091.

587 Bergman, N., Laronne, J. B. and Reid, I., 2007. Technical communication: Benefits of design  
588 modifications for the Birkbeck bedload sampler, illustrated by flash-floods in an ephemeral gravel-bed  
589 channel. *Earth Surface Processes and Landforms*. 32 (2), 317-328.

590 Bravo-Espinosa, M., Osterkamp, W. R. and Lopes, V. L., 2003. Bedload transport in alluvial channels.  
591 *Journal of Hydraulic Engineering*. 129 (10), 783-795.

592 Carson, M. A. and Griffiths, G.A., 1987. Influence of channel width on bedload transport capacity.  
593 *Journal of Hydraulic Engineering*. 113, 1489-1509.

594 Chang, H. H., 1994. Selection of gravel-transport formula for stream modeling. *Journal of Hydraulical*  
595 *Engineering*. 120 (5), 646–651.

596 Chien, N., 1954. The present status of research on sediment transport. *Transaction of the American*  
597 *Society of Civil Engineers*. US Geological Survey Report.

598 Church, M. and Hassan, M. 1992. Size and distance of travel of unconstrained clasts on a streambed.  
599 *Water Resources Research*. 28 (1), 299-303.

600 Church, M. and Hassan, M., 2005. Upland gravel-bed rivers with low sediment transport. In: García,  
601 C. and Batalla, R. J. (eds). *Catchment dynamics and river processes: Mediterranean and other climate*  
602 *regions*. Elsevier, Amsterdam, pp. 141-168.

603 Csoma, J., 1973. Reliability of bed-load sampling. *Proceedings 23rd Meeting, International*  
604 *Association of Hydraulic Research*, 2, Delft (Holland), pp. 97-107.

605 D'Agostino, V. and Lenzi, M. A. (1999). Bedload transport in the instrumented catchment of the Rio  
606 Cordon: Part II. Analysis of the bedload rate. *Catena*. 36, 191-204.

607 De Vries, P. E. (1973). On measuring discharge and sediment transport in rivers. *Publication No. 106*.  
608 *Delft Hydraulics Laboratory*. Delft (Holland).

609 Dietrich, W. E., Kirchner, J. W., Ikeda, H. and Iseya, F. 1989. Sediment supply and the development  
610 of the coarse surface layer in gravel-bedded rivers. *Nature*. 340, 215-217.

611 Du Boys, M.P. 1879. Etudes du regime et l'action exercé par les eaux sur un lit à fond de graviers  
612 indéfiniment affouiable. *Ann. Ponts Chaussees*. 5(18), 141-195.

613 Dufour, S. and Piègay, H., 2009. From the myth of a lost paradise to targeted river restoration: forget  
614 natural references and focus on human benefits. *River Research and Applications*. 25 (5), 568-581.

615 Einstein, H. A., 1950. The bed-load function for sediment transportation in open-channel flows.  
616 *Technical bulletin of the US Department of Agriculture Soil Conservation Service*, 1026. Washington  
617 D.C., USA.

618 Ferguson, R. I. (2005). Estimating critical stream power for bedload transport calculations in gravel-  
619 bed rivers. *Geomorfology*. 70, 33-41.

620 Fernández , E. and Anadón, S. 2010. Análisis de encajamiento en los ríos Nalón (Asturias) y Carrión  
621 (Palencia) en las últimas décadas y repercusión en la inundabilidad. In: Úbeda, X., Vericat, D. y

622 Batalla, R. J. (eds.). Avances de la Geomorfología en España (2008-2010). XI Reunión Nacional de  
623 Geomorfología. S.E.G., Solsona, pp. 365-368.

624 Fernández, E., Tirador, P. and Marquinez, J. 2006. Impacto de las canalizaciones en el río Narcea  
625 (Asturias). In: Pérez Alberdi, A. y Bedoya, J. L. (eds.), Geomorfología y Territorio. IX Reunión  
626 Nacional de Geomorfología. S.E.G., Santiago de Compostela, pp. 509-520.

627 Frostick, L.E. and Jones, S.J., 2002. Impact of periodicity on sediment flux in alluvial systems; grain  
628 to basin scale. In: Frostick, L.E. and Jones, S.J. (eds.). Sediment Flux to Basins: Causes, Controls and  
629 Consequences. Geological Society, London, Special Publication 191, pp. 81-95.

630 García, C and Sala, M. (1998). Aplicación de fórmulas de transporte de fondo a un río de gravas:  
631 comparación con las tasas reales de transporte obtenidas en el río Tordera. Ingeniería del Agua. 5 (1),  
632 59-72.

633 García, C, Laronne, J. B. and Sala, M. 1999. Variable source areas of bedload in a gravel-bed stream.  
634 Journal of Sedimentary Research. 69 (1), 27-31.

635 García, C., Laronne, J. B. and Sala, M., 2000. Continuous monitoring of bedload flux in a mountain  
636 gravel-bed river. Geomorphology. 34, 23-31.

637 Gomez, B. (1991). Bedload transport. Earth Science Reviews. 31, 89-132.

638 Gomez, B. and Church, M. 1989. An assessment of bed load sediment transport formulae for gravel  
639 bed rivers. Water Resources Research. 25 (6), 1161-1186.

640 Graf, W.H., 1971. Hydraulics of sediment transport. McGraw Hill, New York.

641 Gyr, A. and Hoyer, K., 2006. Sediment transport: a geophysical phenomenon. Springer-Verlag, Berlin  
642 (Germany).

643 Habersack, H. M. and Laronne, J. B., 2002. Evaluation and improvement of bedload discharge  
644 formulas based on Helley-Smith sampling in an alpine gravel bed river. Journal of Hydraulic  
645 Engineering. 128 (5), 1-16.

646 Haschenburger, J. K., 1996. Scour and fill in a gravel-bed channel: observations and stochastic  
647 models. PhD Thesis. University of British Columbia. Vancouver.

648 Haschenburger, J. K. and Church, M., 1998. Bed material transport estimated from the virtual velocity  
649 of sediment. Earth Surface Processes and Landforms. 23, 791-808.

650 Hassan, M. A. and Ergenzinger, P., 2003. Use of tracers in fluvial geomorphology. In: Kondolf, G. M.  
651 and Piégay, H. (eds). Tools in fluvial geomorphology. John Wiley and Sons, Chichester, pp. 397-423.

652 Hassan, M. A., Church, M. and Ashworth, P. J., 1992. Virtual rate and mean distance of travel of  
653 individual clasts in gravel-bed channels. *Earth Surface Processes and Landforms*. 17, 617-627.

654 Helly, E. J. and Smith, W., 1971. Development and calibration of a pressure-difference bedload  
655 sampler. US Geological Survey Open-File Report.

656 Hicks, D. M. and Gomez, B. (2003). Sediment transport. In: Kondolf, G. M. and Piégay, H. (eds).  
657 Tools in fluvial geomorphology. John Wiley and Sons, Chichester, pp. 425-461.

658 Hoey, T. and Sutherland, A., 1991. Channel morphology and bedload pulses in braided rivers: a  
659 laboratory study. *Earth Surface Processes and Landforms*. 16, 447-462.

660 Kirchner, J. W., Dietrich, W. E., Iseya, F. and Ikeda, H. (1990). The variability of critical shear stress,  
661 friction angle and grain protrusion in water-worked sediments. *Sedimentology*. 37, 647-672.

662 Laronne, J. B., Reid, I., Yitshack, Y. and Frostick, L. E., 1992. Recording bedload discharge in a  
663 semiarid channel, Nahal Yatir, Israel. In: Bogen, J.; Walling, D. E. y Day, T. J. (eds.). *Erosion and*  
664 *Sediment Transport monitoring programmes in river basins*. International Association of Hydrological  
665 Sciences Publication, Vol. 210, pp. Oslo, 79-86.

666 López, R., Vericat, D. and Batalla, R.J., 2013. Evaluation of bed load transport formulae in a large  
667 regulated gravel bed river: the lower Ebro (NE Iberian Peninsula). *Journal of Hydrology*. 510, 164-  
668 181.

669 Martin, Y., 2003. Evaluation of bed load transport formulae using field evidence from the Vedder  
670 River, British Columbia. *Geomorphology*. 53, 75-95.

671 Martin, Y. and Church, M., 2000. Re-examination of Bagnold's empirical bedload -formulae. *Earth*  
672 *Surface Processes and Landforms*. 25 (9), 1011-1024.

673 Martin, Y. and Ham, D., 2005. Testing bed load transport formulae using morphologic transport  
674 estimates and field data: lower Fraser River, British Columbia. *Earth Surface Processes and*  
675 *Landforms*. 30, 1265-1282.

676 Martínez Marín, E. 2001. *Hidráulica fluvial: principios y práctica*. Editorial Bellisco, Madrid.

677 Meyer Peter, R. and Müller, R., 1948. Formulas for bedload transport. Proceedings 2nd Meeting,  
678 International Association of Hydraulic Research, Stockholm, pp. 39-64.

679 Meirovich, L., Laronne, J. B. and Reid, I. (1998). The variation of watersurface slope and its  
680 significance for bedload transport during floods in gravel bed streams. *Journal of Hydraulic*  
681 *Engineering*. 36 (2), 147-157.

682 Parker, G. 1979. Hydraulic geometry of active gravel rivers. *Journal of Hydraulic Engineering*. 105,  
683 1185-1201.

684 Parker, G. 1990. Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic*  
685 *Research*. 28 (4), 417-436.

686 Parker, G. 2008. Chapter 3: Transport of gravel and sediment mixtures. In: García, M. (ed.). *Manual*  
687 *110. Sedimentation engineering: processes, measurements, modelling and practice*. American Society  
688 of Civil Engineers, Virginia, pp. 165-244.

689 Parker, G. and Klingeman, P.C., 1982. On why gravel bed streams are paved. *Water Resources*  
690 *research*. 18 (5), 1409-1423.

691 Parker, G., Klingeman, P.C. and McLean, D. G., 1982. Bedload and size distribution in paved gravel-  
692 bed stream. *Journal of the Hydraulics Division of the American Society of Civil Engineers*. 108 (4),  
693 544-571.

694 Pitlick, J., Cui, Y. and Wilcock, P., 2009. *Manual for computing bed load transport using BAGS*.  
695 USDA, Forest Service, Rocky Mountain Research Station, Colorado (USA).

696 Rascher, E., Baewert, H., Schmidt, K. H. and Morche, D. (2012). Comparing the results of transport  
697 equations to field measurements in an Alpine river. *Geophysical Research Abstracts*, 14, EGU2012-  
698 9763.

699 Recking, A. (2010). A comparison between flume and bed load transport data and consequences for  
700 surface-based bed load transport prediction. *Water Resources Research*. 46, 1-16.

701 Recking, A., Liébault, F., Peteuil, C. and Jolimet, T., 2012. Testing bedload transport equations with  
702 consideration of time scales. *Earth Surface Processes and Landforms*. 37 (7), 774-789.

703 Reid, I., Lareonne, J. B. and Powell, D. M., 1995. The Nahal-Yatir bedload database: sediment  
704 dynamics in a gravel-bed ephemeral stream. *Earth Surface Processes and Landforms*. 20 (9), 845-857.

705 Reid, I., Powell, D. M. and Laronne, J. B. 1996. Prediction of bed-load transport by desert flash  
706 floods. *Journal of Hydraulic Engineering*. 122, 170-173.

707 Rennie, C. D., Millar, R. G. and Church, M. A., 2002. Measurement of bed load velocity using an  
708 acoustic Doppler current profiler. *Journal of Hydraulic Engineer*. 128 (5), 473–483.

709 Rickenmann, D., 1997. Sediment transport in Swiss torrents. *Earth Surface Processes and Landforms*.  
710 22, 937-951.

711 Schoklitsch, A. (1934). *Der geschiebetrieb und die geschiebefracht*, *Wasserkraft Wasserwirtschaft*. 4,  
712 1-7.

713 Schoklitsch, A., 1950. *Handbuch des Wasserbaues*. Springer-Verlag, New York.

714 Shields, A. (1936). *Ähnlichkeitmechanik und der Turbulenzforschung auf die Geschiebebewegung*.  
715 *Mitteilungen der Preussischen Versuchsanstalt für Wasserbau und Schiffbau*, 26. Translated to  
716 english by Ott, W.P. and van Uchelen, J.C. CalTech, Pasadena, California.

717 Shulits, S., and Hill, R. D., 1968. *Bedload formulas*. Agricultural Research Service, U.S. Department  
718 of Agriculture, Washington, D.C.

719 Sterling, S. M. and Church, M., 1992. Sediment trapping characteristics of a pit trap and the Helley  
720 Smith sampler in a cobble gravel bed river. *Water Resources Research*. 38 (8), 1144-1155.

721 Straub, L. G. 1935. *Missouri River report, Appendix 15*. In-House Document 238. 73th Congress, 2nd  
722 Session. Washington D.C.

723 Vázquez, D., Menéndez, R. and Fernández, E. 2012. Changes in fluvial sediment storage from aerial  
724 photograph analysis (river Narcea, Northern Cantabrian Range). *Cuaternario y Geomorfología*. 25 (3-  
725 4), 71-85.

726 Vázquez-Tarrio, D., 2013. *Transporte de sedimento como carga de fondo en la cuenca del río Narcea*  
727 *(vertiente Norte de la Cordillera Cantábrica)*. Ph. D. Thesis, University of Oviedo. Oviedo (Spain).

728 Vázquez-Tarrio, D. and Menéndez-Duarte, R., 2014. Bedload transport rates for coarse-bed streams in  
729 an Atlantic region (Narcea River, NW Iberian Peninsula). *Geomorphology*. 217, 1-14.

730 Venditti, J. G., Nelson, P. A. and Dietrich, W. E. 2008. The domain of bedload sheets. In: Parsons, D.,  
731 Best, J. L. and Trentesaux, A. (eds). *Marine Seawater and River Dune Dynamics III*. Leeds University,  
732 Leeds, pp. 315-321.

733 Vericat, D., Batalla, R. J. and García, C., 2006. Breakup and reestablishment of the armour layer in a  
734 large gravel-bed river below dams: the lower Ebro. *Geomorphology*. 76, 122-136.

735 Wilcock, P. R. 1993. Critical shear stress of natural sediment. *Journal of Hydraulic Engineering*. 119  
736 (4), 491-505.

737 Wilcock, P. R. and Crowe, J. C., 2003. Surface-based transport model for mixed-size sediment.  
738 *Journal of Hydraulic Engineering*. 129 (2), 120-128.

739 Wilcock, P. R., Kenworth, S. T. and Crowe, J. C., 2001. Experimental study of the transport of mixed  
740 sand and gravel. *Water Resources Research*. 37 (12), 3349-3358.

741 Wilcock, P., Pitlick, J. and Cui, Y., 2009. Sediment transport primer: estimating bed-material transport  
742 in gravel bed rivers. USDA, Forest Service, Rocky Mountain Research Station, Colorado, USA.

743 Wittenberg, L. and Newson, M. D., 2005. Particle clusters in gravel-bed rivers: an experimental  
744 morphological approach to bed material transport and stability concepts. *Earth Surface Processes and*  
745 *Landforms*. 30, 1351-1368.

746 Wong, M. and Parker, G., 2006. Re-analysis and corrections of bedload relation of Meyer-Peter and  
747 Müller using their own database. *Journal of Hydraulic Engineering*. 132 (11), 1159-1168.

748 Yager, E.M., Kirchner, J. W. and Dietrich, W. E., 2007. Calculating bed load transport in steep  
749 boulder-bed channels. *Water Resources Research*. 43, 1-24.

750 Yager, E.M., Dietrich, W. E., Kirchner, J. W. and McArdell, B. W., 2012. Prediction of sediment  
751 transport in step-pool channels. *Water Resources Research*. 48, 1-20.

752 **CAPTIONS**

753 **Figure 1.** (A) Location of River Narcea drainage basin in the northern Cantabrian Range  
754 watershed. (B) Location of the studied reaches (Rivers Pigüeña and Coto) and gauge stations  
755 along the River Narcea basin.

756 **Figure 2.** A) River Pigüeña lateral bar B) River Coto channel and lateral bar.

757 **Figure 3.** Comparison between bedload rates estimated through the different equations (y-axis),  
758 and the bedload rates derived from tracer experiment (x-axis). The 9 plots show the results  
759 obtained with each one of the 9 bedload equations assessed here: Du Boys-Straub (DB-S);  
760 Schoklitsch (SC); Meyer Peter-Müller (MP-M); Einstein (EI); Bagnold (BA); Parker-  
761 Klingemann-McLean (P-K-MC); Parker-Klingemann (P-K); Parker (P); Wilcock-Crowe(W-C).

762 **Figure 4.** Bedload rating curve built using each theoretical equation, compared with the bedload  
763 rating curve derived from the experimental fit (River Pigüeña): Du Boys-Straub (DB-S);  
764 Schoklitsch (S); Meyer Peter-Müller (MP-M); Einstein (EI); Bagnold (BA); Parker-  
765 Klingemann-McLean (P-K-MC); Parker-Klingemann (P-K); Parker (P); Wilcock-Crowe(W-C).  
766 Dotted lines show the values which represent a ratio of 10, 100, 1000...times the results  
767 obtained with the experimental fit.

768 **Figure 5.** Bedload rating curve built using each theoretical equation compared, with the bedload  
769 rating curve derived from the experimental fit (River Coto): Du Boys-Straub (DB-S);  
770 Schoklitsch (S); Meyer Peter-Müller (MP-M); Einstein (EI); Bagnold (BA); Parker-  
771 Klingemann-McLean (P-K-MC); Parker-Klingemann (P-K); Parker (P); Wilcock-Crowe(W-C).  
772 Dotted lines show the values which represent a ratio of 10, 100, 1000...times the results  
773 obtained with the experimental fit.

**Table 1.** Main features of the studied transport episodes (Vázquez-Tarrió and Menéndez-Duarte, 2014).

<b>Date</b>	<b>River</b>	<b>Main peak time duration (h)</b>	<b>Maximum mean discharge (m<sup>3</sup>/s)</b>	<b>Maximum peak discharge (m<sup>3</sup>/s)</b>	<b>Basal shear stress (Pa)</b>
15-18 January 2010	River Pigüehña	72.00	32.0	103.5	114.8
10 – 24 June 2010	River Pigüehña	102.25	80.4	100.0	112.1
31 October -20 November 2010	River Pigüehña	43.00	78.7	107.5	117.6
13-16 Januray 2010	River Coto	96.00	26.9	28.4	131.0
11 – 17 June 2010	River Coto	46.75	27.6	30.1	135.4
6 -8 January 2011	River Coto	44.25	25.4	25.6	130.7

**Table 2.** Bedload transport rates obtained with the tracer experiment in River Pigüeña and River Coto (Vázquez-Tarrío and Menéndez-Duarte, 2014). Unit transport rate are the transport rates per unit of width of channel.

<b>Flood episode</b>	<b>Studied channel</b>	<b>Measured transport rates (kg/s)</b>	<b>Unit transport rates (kg/m·s)</b>
January 2010	River Pigüeña	4,06	0,10
June 2010	River Pigüeña	2,54	0,06
November 2010	River Pigüeña	1,10	0,03
January 2010	River Coto	0,20	0,01
June 2010	River Coto	0,21	0,01
January 2011	River Coto	0,28	0,01

**Table 3.** Summary of the results obtained comparing bedload transport rates estimated using the equations, and the bedload rates obtained in the field with tracers. Results for River Pigüena.

	Estimated bedload rates (kg/s)			Discrepancy Ratios			
	January 2010	June 2010	November 2010	January 2010	June 2010	November 2010	Geometric mean
<i>Du Boys- Straub</i>	4526.4	4312.4	4753.9	1116	1696	4337	<b>2017.2</b>
<i>Schoklitsch</i>	316.4	298.4	335.1	78	117	306	<b>140.9</b>
<i>Meyer Peter- Müller</i>	481.0	453.5	509.4	118	178	464	<b>213.6</b>
<i>Einstein</i>	845.6	789.1	904.7	208	310	824	<b>376.3</b>
<i>Bagnold</i>	88.5	83.6	94.3	22	33	86	<b>39.5</b>
<i>Parker- Klingeman -MacLean</i>	100.2	91.1	110.1	25	36	101	<b>44.6</b>
<i>Parker- Klingeman</i>	32.6	26.6	39.9	8	11	36	<b>14.5</b>
<i>Parker</i>	18.7	15.8	22.2	5	6	20	<b>8.3</b>
<i>Wilcock- Crowe</i>	3.6	3.0	4.3	1	1	4	<b>1.6</b>
<i>Eq. (1)</i>	2.2	1.8	2.5	1	1	2.3	<b>0.9</b>

**Table 4.** Summary of the results obtained comparing bedload transport rates estimated using the equations and the bedload rates obtained in the field with tracers. Results for River Coto.

	Estimated bedload rates (kg/s)			Discrepancy Ratios			
	January 2010	June 2010	January 2011	January 2010	June 2010	January 2011	Geometric mean
<i>Du Boys-Straub</i>	4101.1	4449.9	4101.1	20725	20876	14907	<b>18614.2</b>
<i>Schoklitsch</i>	544.1	585.4	541.0	2749	2746	1966	<b>2457.8</b>
<i>Meyer Peter-Müller</i>	647.6	697.5	643.9	3272	3273	2340	<b>2926.3</b>
<i>Einstein</i>	294.4	331.6	291.7	1488	1556	1060	<b>1349.0</b>
<i>Bagnold</i>	18.4	21.7	12.8	93	102	47	<b>76.1</b>
<i>Parker-Klingeman-MacLean</i>	2.4	4.1	2.3	12	19	9	<b>12.5</b>
<i>Parker-Klingeman</i>	3.9	6.2	3.7	20	19	14	<b>17.2</b>
<i>Parker</i>	63.9	78.3	62.9	323	367	229	<b>300.4</b>
<i>Wilcock-Crowe</i>	10.1	12.6	10.0	51	59	36	<b>47.8</b>
<i>Eq. (1)</i>	0.2	0.3	0.2	1	1	1	<b>1.0</b>

**Table 5.** Performance of the formulae compared with a selection of recent studies in gravel bed streams.

Reference	$N^a$	$r(0.5-2)^b$ %	$r(0.2-5)^c$ %	$r(0.1-10)^d$ %	Observations
Batalla (1997) <sup>e</sup>	5	50	-	-	Bed-material load in a sandy, gravel bed river.
Habersack and Laronne (2002) <sup>e</sup>	13	36	-	-	Alpine gravel bed river
Martin (2003) <sup>f</sup>	4	19	44	75	Annual transport in 10 reaches of a gravel-bed river
Martin and Ham (2005) <sup>e, f</sup>	3	11	25	47	Average annual transport in 13 reaches of a gravel bed stream
Duan et al. (2006) <sup>e</sup>	3	-	-	57	Low flow in two reaches of a desert gravel bed stream
Recking (2010) <sup>g</sup>	4	13	27	34	6319 data from 84 reaches of sand and gravel bed rivers, and flume experiments
Rascher (2012) <sup>e</sup>	16	-	-	19	Bedload rates in a coarse-bed river from Bavaria
Rascher (2012)*	7	-	-	25	Bedload rates in a coarse-bed river from Bavaria
López et al. (2014) <sup>e</sup>	10	19	41	57	Regulated river experiencing cycles of armoring
This study	9	4	7	13	Bedload rates for flows in two mountain coarse bed streams
This study*	4	8	17	29	Bedload rates for flows in two mountain coarse bed streams

<sup>a</sup> Number of formulas tested in the paper.

<sup>b</sup>  $0.5 < r < 2$ , the average percentage of predicted bed load discharge not exceeding a factor of 2 in relation to the observed discharge.

<sup>c</sup>  $0.2 < r < 5$ , the average percentage of predicted bed load discharge not exceeding a factor of 5 in relation to the observed discharge.

<sup>d</sup>  $0.1 < r < 10$ , the average percentage of predicted bed load discharge not exceeding a factor of 10 in relation to the observed discharge.

<sup>e</sup> Measurements with a Helley-Smith/basket sampler.

<sup>f</sup> Annual bedload yields obtained using the morphological approach.

<sup>g</sup> Assessment accomplish using field data taken from the scientific literature, and their own flume results.

\* The average percentages are calculated only for the 'modern equations', and not for all the equations assessed in the study.

