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► **To cite this version:**

Louis Gilet, Frédéric Gob, E Gautier, Geoffrey Houbrechts, Clément Virmoux, et al.. Hydro-morphometric parameters controlling travel distance of pebbles and cobbles in three gravel bed streams. *Geomorphology*, 2020, 358, pp.107117. 10.1016/j.geomorph.2020.107117 . hal-02612978

**HAL Id: hal-02612978**

**<https://hal.science/hal-02612978>**

Submitted on 20 May 2022

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1 **Hydro-morphometric parameters controlling travel distance of pebbles and cobbles in three**  
2 **gravel bed streams**

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11 **Abstract**

12 This study investigates the parameters controlling bedload distances in several gravel-bed rivers of a  
13 medium mountain (Morvan, France). Using PIT tags introduced into pebbles and cobbles, an  
14 examination of the relationship between several hydro-morphometric variables and travel distance was  
15 first undertaken with bivariate analysis. Bedload distances of our 6 study sites show important  
16 differences and this discrepancy cannot fully be understood considering only the stream power for the  
17 peak discharge, especially in multi-peak surveys such as ours. Stream impulse, a variable combining  
18 flow intensity and flow competence duration, has a stronger correlation with bedload distances. The  
19 analysis also indicates a varying influence of relative grain size, relative flow depth, bed slope and  
20 width/depth ratio. Among all these parameters, in order of importance, the relative grain size, the slope,  
21 and the stream impulse, emerge as the most significant explanatory variables from a multivariate  
22 analysis. The role of the relative grain size on bedload transport underlines the importance of grain size  
23 sorting and microtopography in plane-bed rivers. The influence of the slope is ambivalent: favoring  
24 bedload distances under certain circumstances and lowering them under others. The direction of the  
25 influence of the slope seems to depend on its combination with other morpho-sedimentary or hydraulical  
26 parameters. Finally, we propose a single equation for bedload distance prediction that predicts travel  
27 distance rather well.

28 **Key words**

29 Bedload travel distance; stream impulse; relative grain size; bed slope; gravel-bed rivers; PIT tags

## 30 **1. Introduction**

31 Bedload travel distance and derived bedload velocity are key features of sediment transport and channel  
32 form dynamics. Indeed, bedload velocity controls the rhythm of bar migration (Jaeggi, 1987), pool-bar  
33 sequences (Pryce and Ashmore, 2003a, b), sediment wave propagation (Madej and Osaki, 1996;  
34 Sutherland *et al.*, 2002) and gravel dispersion (Haschenburger, 2011). Bedload distance and velocity are  
35 also used for the calculation of bedload discharge (Laronne *et al.*, 1992; Haschenburger and Church,  
36 1998; Liébault and Laronne, 2008; Houbrechts *et al.*, 2012; 2015; Dell’Agnese *et al.*, 2015; Mao *et al.*,  
37 2017a). However, among the very large amount of papers that discuss bedload transport, few focus on  
38 travel distance and a lot remains to be done to truly understand the parameters that influence bedload  
39 distances and transport velocity.

40 Particle size is of course a fundamental component to consider when studying sediment transport, for  
41 entrainment conditions as well as for displacement length (Robert, 2003). Most of the studies using  
42 tracing techniques show that smaller particles tend to cover larger displacements than coarser fractions  
43 of the tracers (Hassan *et al.*, 1991; Church and Hassan, 1992. Lenzi, 2004; Scheingross *et al.*, 2013;  
44 Schneider *et al.*, 2014). Ferguson and Wathen (1998) emphasized, however, that the influence of the  
45 grain size on travel distances (inverse correlation) was more significant for the coarsest fractions of the  
46 riverbed substrate. Wilcock (1997) and Lenzi (2004) observed in their studies that displacement length  
47 was dependent on the particle size only for coarser sediment moving under partial transport conditions.  
48 It was independent of the grain size for smaller, fully mobile grain size fractions. On their side, Church  
49 and Hassan (1992) found that the inverse correlation between travel distance and particle size was less  
50 obvious for smaller grain-size fractions because they were more frequently and more efficiently trapped  
51 within substrate arrangements (buried, locked or constrained within an imbricated structure).

52 When reviewing the literature, it also appears that the time scale is key when analyzing the relationship  
53 between travel distance and grain size. Phillips and Jerolmack (2014) observe a solid inverse correlation  
54 between distance and grain size for cumulated displacement length after many hydrological events,  
55 whereas the same inverse correlation is weak for the individual flood scale. A poor correlation between  
56 grain size and virtual velocity of tagged particles is also observed by Mao *et al.* (2017b) on a short time

57 scale study. Beyond the grain size factor, bedload propagation rates tend to slow down with time  
58 (Ferguson *et al.*, 2002), with vertical mixing and progressive burial of the gravel greatly contributing to  
59 its slowdown. This is obviously strongly connected to the magnitude and frequency of flood events  
60 (Houbrechts *et al.*, 2015). But storage of gravel in less active and lower energy zones such as point bars,  
61 plunge pools and logjams may also moderate the particle displacement (Pyrce and Ashmore, 2005;  
62 Houbrechts *et al.*, 2015).

63 Some studies evaluate the relationship between bedload displacement length and hydrological, hydraulic  
64 and morphological parameters that are known to affect or reflect rivers' energy, flow resistance and/or  
65 particle resistance to entrainment (Church and Hassan, 1992; Hassan and Church, 1992; Lenzi, 2004;  
66 Liébault and Clement, 2007; Lamarre and Roy, 2008; Milan, 2013; Phillips and Jerolmack, 2014;  
67 Houbrecht *et al.* 2015; Papangelakis and Hassan, 2016; Klösch and Habersack, 2018). Most of these  
68 authors analyze their displacement results in relation to the excess energy above threshold conditions  
69 (number of mobilizing floods, competent flow duration, discharge, velocity, specific stream power, shear  
70 stress, *etc.*) but such a relationship is still not yet clearly established (Hassan and Bradley, 2017).

71 This study explores the hydrological and morphological parameters that control the bedload travel  
72 distances in three French gravel-bed rivers. In the medium-sized Morvan mountain (central France), our  
73 research investigates the role of relative grain size, bed slope, relative flow depth, width/depth ratio,  
74 energy magnitude and flow duration on travel distance on plane-bed rivers. To do so, bedload transport  
75 was studied on six study sites among three different rivers, all located in the same regional morpho-  
76 climatic context. The influence of specific hydro-morphometric characteristics on bedload transport  
77 processes at-a-site scale is explored. For every site, we undertook a two-steps analysis: (i) simple  
78 bivariate analysis in order to test the influence of the control parameters on the bedload distance;  
79 followed by (ii) a multivariate analysis allowing a single relationship for travel distance prediction to be  
80 proposed for all of our studied rivers.

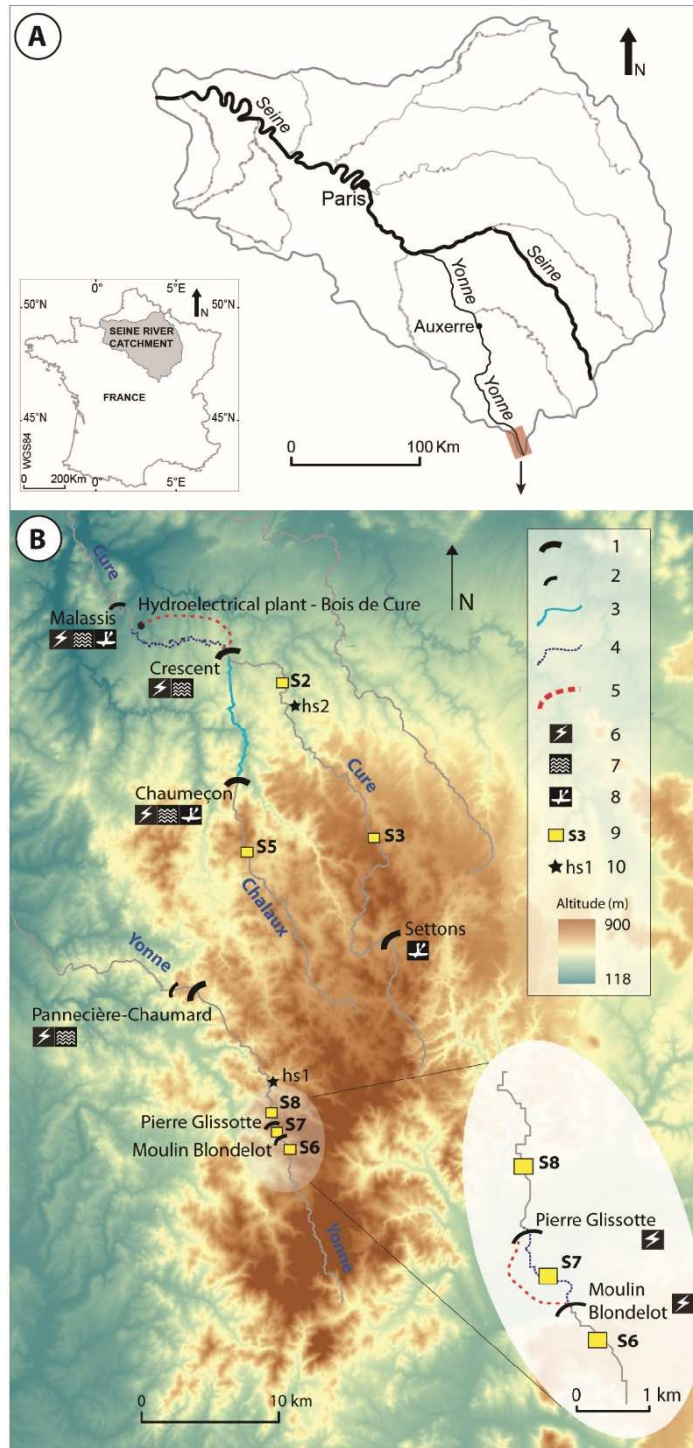
## 81 2. Study sites

82 The Morvan massif is a hercynian medium mountain located in the southeast of the Seine catchment  
83 (central France) where maximum relief elevation reaches 902 m. (Fig. 1A-B). Its substratum is mainly  
84 granitic and gneissic rocks and its climate is temperate oceanic with pluviometry influenced by the  
85 orography. The mean annual precipitation in the region is about 900 mm. Combined with the  
86 imperviousness of the substratum, this has led to the formation of a channel network featuring a high  
87 drainage density.

88 Six river reaches of three gravel-bed rivers of this region were studied: three on the Yonne river (between  
89 388 and 343 m elevation and, 71 and 83 km<sup>2</sup> for the drainage area), two on the Cure river (between 445  
90 and 295 m elevation, and 160.5 and 234 km<sup>2</sup>) and one on the Chalaux river (approximately 395 m  
91 elevation, and 69 km<sup>2</sup>) (Fig. 1B). They may be considered as medium energy streams with specific  
92 stream power for the bankfull discharge fluctuating between 45 and 167 W/m<sup>2</sup> for slopes ranging from  
93 0.0056 m/m to 0.015 m/m (Table 1). The order of the grain size distribution of the bed corresponds  
94 rather well to that of the slope values (Table 1). The bed D<sub>50</sub> and D<sub>84</sub> range respectively between 0.074  
95 and 0.265 m and 0.105 and 0.699 m, indicating riverbeds dominated by cobbles or small boulders (Table  
96 1 and Fig. 2). With the exception of site S3, our study sites are rather homogeneous and present  
97 morphologies that could be qualified as plane-bed. On S3, the grain size distribution is wider and the  
98 bed morphology tends to resemble either a light step-pool system or a transverse ribs system (Fig. 2B).  
99 Finally, it should be pointed out that the hydrological regimes of some of our study sites are not quite  
100 natural as the hydrological regimes are regulated by the releases of a large dam upstream of the Cure  
101 river (Settons dam, built in 1858) and by two smaller ones on the Yonne River (Pierre Glissotte and  
102 Moulin Blondelot dams, built in the mid-1920s) (Fig. 1B).

103

104



107 **Fig. 1. Locations maps: A) The Morvan massif in the Seine river catchment, B) The study sites**  
 108 **on the Yonne and Cure rivers.**

109 1. Large dams (> 15 m); 2. Medium size dams (< 10 m); 3. Regular water-releases; 4. By-  
 110 passed canal; Dam function: 6. Hydroelectricity; 7. Flood control; 8. Nautical sports; 9. Study site; 10. Hydrometric  
 111 station.

113 **Table 1. Characteristics of the study sites**  
 114

Site number and river	S2 Cure	S3 Cure	S5 Chaloux	S6 Yonne	S7 Yonne	S8 Yonne
Catchment area (km <sup>2</sup> )	234	160.5	69	71	74,5	83
Mean annual discharge (m <sup>3</sup> /s)	4.76	3.51	1.65	1.84	1.93*	2.15
Bankfull discharge (m <sup>3</sup> /s)	20.5	16	6.2	6	5.5	9.5
Specific stream power for bankfull discharge (W/m <sup>2</sup> )	78	166.7	48	45.2	77.1	67.7
Bankfull width (m)	18.05	14.12	7.1	9.5	10.5	11.7
Bed slope (m/m)	0.007	0.015	0.0056	0.0073	0.015	0.0085
D <sub>50</sub> (m)	0.133	0.265	0.080	0.074	0.108	0.083
D <sub>84</sub> (m)	0.224	0.699	0.142	0.105	0.247	0.175
D <sub>16</sub> (m)	0.051	0.041	0.023	0.034	0.038	0.037
D <sub>84</sub> /D <sub>16</sub> (sorting index)	4.41	17.17	6.17	3.09	6.50	4.69

115  
 116 \* Reconstructed natural flow, if there was not a diversion of the discharge from the upstream Moulin Blondelot  
 117 dam.  
 118

119



A-S2 Cure



B-S3 Cure



C-S5 Chaux



D-S6 Yonne



E-S7 Yonne



F-S8 Yonne

120

121 **Fig 2. Photographs of the study sites during low or medium flows.**

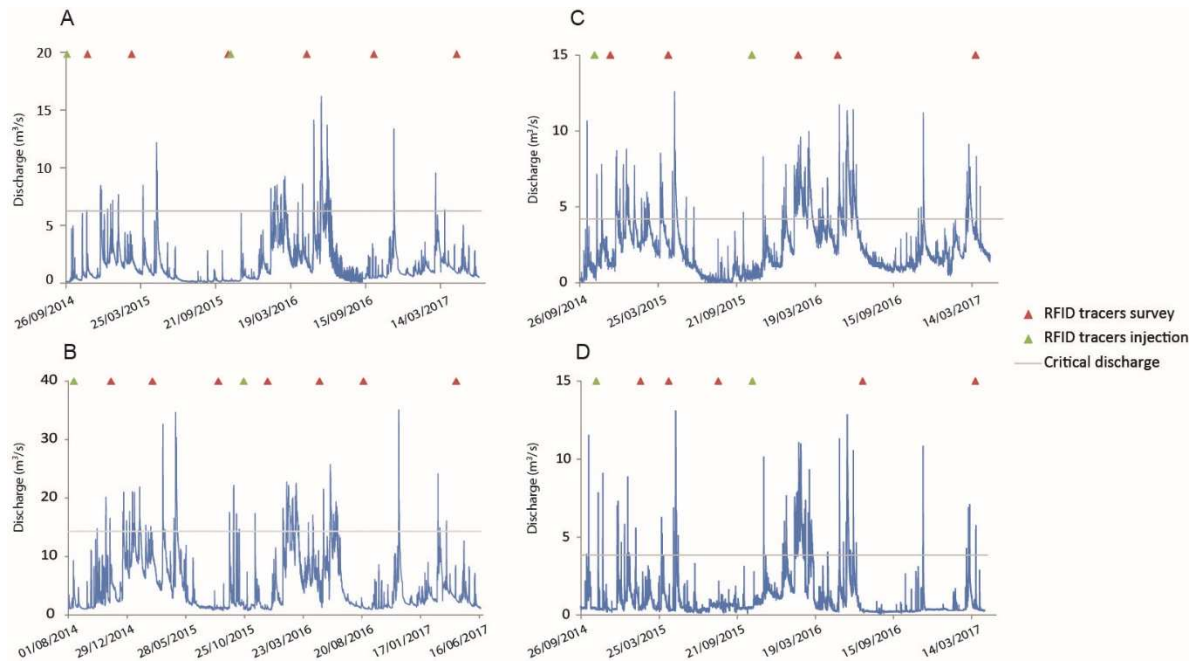
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123

124



125 The Settons dam was built in 1858 in order to float wood logs. It allowed artificial floods to increase the  
126 river's capacity to transport logs that were injected from the river banks at the same time. It is 19 m  
127 high and 267 m wide and has a reservoir of 22.7 Mm<sup>3</sup>. It is located about 17 km and 31 km respectively  
128 upstream of the S3 and S2 study sites. Nowadays, its only function consists of enabling the practice of  
129 nautical sports about 30 days/year thanks to water releases. These water releases are mainly operated in  
130 spring and autumn, in order to reach a 5 m<sup>3</sup>/s discharge on average, and 7/8 m<sup>3</sup>/s very occasionally.  
131 Those values correspond to 30 to 50% of the bankfull discharge at the downstream study sites. Also, the  
132 Settons dam does not control peak flow significantly, as shown on Fig. 3B. This is why the study sites  
133 located downstream (S2 and S3) have been considered as non-influenced in the rest of this paper. This  
134 assessment is also true for S8, which was not influenced hydrologically by the Pierre Glissotte dam (Fig.  
135 1B) because its reservoir was entirely full of sediment preventing any discharge control (Gilet *et al.*,  
136 2018). S8, located 1.3 km downstream, presents therefore the same hydrological regime as the upstream  
137 non-influenced site (S6, Fig. 3C). S7 is the only site that should be considered as moderately influenced  
138 because it is located in a by-passed reach, 300 m downstream of the Moulin Blondelot dam (Fig. 1B).  
139 The maximum by-passed discharge is 2.3 m<sup>3</sup>/s (for a bankfull discharge of 5.5 m<sup>3</sup>/s), but large floods  
140 mainly flow through the by-passed reach as they remain poorly affected by the small size of the reservoir  
141 (700 m<sup>3</sup>) (Fig. 3D). Finally S5 (Fig. 3A) and S6 (Fig. 3C) are located upstream of the dams (Fig. 1B)  
142 and they are thus not hydrologically influenced.



143

144 **Fig. 3. Discharge recorded on S5 Chaux (A), S2 Cure (B), S6 (C) and S7 (D) Yonne sites.** The  
 145 vertical and horizontal axes do not have the same scales on the four graphs and the study period on S2  
 146 begins earlier. The hydrological regime of S2 is the same as S3, located about 14 km upstream and the  
 147 hydrological regime of S6 is the same as S8, located about 6 km downstream. The method for the  
 148 estimation of the critical discharge (for sediment entrainment) is detailed in section 3.1.

### 149 3. Methods

#### 150 3.1 Hydrological monitoring

151 Two public hydrometric stations provide instantaneous discharges: one located on the Yonne river, 3.3  
 152 km downstream of the Pierre Glissotte dam and the other on the Cure river, 28 km downstream of the  
 153 Settons dam (Fig. 1B). In addition, water sensors (Diver, ©Schlumberger) were installed at the upstream  
 154 and downstream limits of the 6 study sites. They recorded water level variations every 15 minutes.  
 155 Coupled with a DEM built from topographical surveys (section 3.2), the upstream and downstream water  
 156 altitude enabled the reach averaged water depth to be calculated for a given discharge using the HEC-  
 157 RAS software.

158 Water levels from water sensors were transformed into discharges with stage-discharge relationships  
 159 built from our own discharge measurements (electro-magnetic current-meter) and extrapolation from  
 160 the two public hydrometric stations (using the catchment area-discharge relationship found in Bravard  
 161 and Petit, 1997). Even though extrapolation always brings uncertainties, comparisons with reference  
 162 values (extrapolated discharges and our own discharge measurements) gives us a high level of

163 confidence in our stage-discharge relationships (between 25 and 28 compared values per site; P-value  
 164 min:  $2.2e-16$  <, P-value max:  $4.8e-14$ ;  $0.93 \leq R^2 \leq 0.99$ ).  
 165 The “energy” of the flow was assessed through the calculation of several parameters. Firstly, the specific  
 166 stream power of the maximum peak discharge that occurred between two surveys of marked particles  
 167 was calculated. The specific stream power was calculated using Bagnold’s (1980) equation:

$$\omega = \rho g Q S / w \quad (1)$$

168 with  $\rho$  the density of water ( $\text{kg/m}^3$ );  $g$  the acceleration due to gravity ( $\text{m/s}^2$ ),  $Q$  the discharge ( $\text{m}^3/\text{s}$ ),  $S$   
 169 the slope ( $\text{m/m}$ ) and  $w$  the width of the water-surface ( $\text{m}$ ).

170 In order to consider the entire amount of energy exerted on the bed, the stream power and duration of  
 171 the peak flows of secondary flood events may also be considered. To do so, integration of flow  
 172 competence duration was undertaken in diverse contexts over the last thirty years in order to analyze  
 173 bedload transport and virtual velocity (Hassan *et al.*, 1992; Gintz *et al.*, 1996; Ferguson and Wathen,  
 174 1998; Ferguson *et al.*, 2002; Milan, 2013; Phillips and Jerolmack, 2014; Schneider *et al.*, 2014;  
 175 Houbrechts *et al.*, 2015; Arnaud *et al.*, 2017; Klösch and Habersack, 2018). In this study we proposed a  
 176 variant of the dimensionless impulse ( $I_*$ ) introduced by Phillips *et al.* (2013) and Phillips and Jerolmack  
 177 (2014), and expressed as:

$$I_* = \int_{ts}^{tf} \frac{(U_* - U_{*c}) dt}{D_{50}}, \quad U_* > U_{*c} \quad (2)$$

178 with  $U_*$  the shear velocity and  $U_{*c}$  the threshold shear velocity for sediment motion,  $D_{50}$  the median grain  
 179 size of the tracers,  $ts$  and  $tf$  the starting and finishing times of the considered period. According to  
 180 equation (2), the excess of shear velocity is considered during the delimited period during which  
 181 sediment transport occurs. These excess values are multiplied by the duration ( $dt$ ) they are supposed to  
 182 last and normalized by the  $D_{50}$  of the tracers mobilized. In this way, the intensity and duration of the  
 183 mobilizing flow as well as the particle size is taken into account to examine the river energy consumed  
 184 for particle transportation. In this study, uncertainties with regard to the calculation of velocities led us

185 to prefer considering specific stream power instead of shear velocity. Consequently, we use an overall  
186 time-integrated excess stream power called “stream impulse” (SI expressed in  $\text{Ws/m}^3$ ). It can be written  
187 as:

$$SI = \int_{t_s}^{t_f} \frac{(\omega - \omega_c) dt}{D_{50}}, \quad \omega > \omega_c \quad (3)$$

188 with  $\omega$  as described in equation (1). In this form SI is rather similar to the excess flow energy expenditure  
189 calculated by Haschenburger (2013) and Schneider *et al.* (2014) that reflects the same idea of calculating  
190 a time-integrated excess stream power (Hassan and Bradley, 2017). Mao *et al.* (2017b) also show the  
191 importance of considering the whole flow series in order to underline the influence of high antecedent  
192 flows on incipient motion of sediments and on their virtual velocity.

193 The slope and width needed for the calculation of stream power are both known from topographical  
194 surveys: the former corresponds to the reach averaged bed slope and the latter to the reach averaged  
195 bankfull width. Critical stream power is calculated from the critical discharge. This is a key parameter  
196 as it conditions the whole calculation of excess energy consumed for particle displacement. Incipient  
197 motion may be approached empirically using PIT tags and a mobile antenna, but this requires multiple  
198 surveys after single low to moderate peak flows. Considering the aims of this study, we have chosen to  
199 focus instead on longer time series that include several moderate and high peak flows. Consequently,  
200 the lowest mobilizing peak discharge ( $Q_{\text{imp}}$ ) we may use to determine critical conditions remains for  
201 some study sites rather high and the distances covered by the tracers after this peak are relatively long.  
202 When compared to the bankfull discharge ( $Q_{\text{bf}}$ ),  $Q_{\text{imp}}$  fluctuates between  $0.83 \cdot Q_{\text{bf}}$  and  $1.15 \cdot Q_{\text{bf}}$  on our 6  
203 study sites for a wide grain size of tagged particles including the large ones (following the study sites,  
204 between  $D_2$  and  $D_6$  of the tracers’ distribution for the finest mobilized grains, to  $D_{86}$  and  $D_{96}$  for the  
205 coarsest ones). The literature shows that these values are very likely excessive and rather indicates that  
206 critical discharges range between  $0.25$  and  $0.8 \cdot Q_{\text{bf}}$  (Andrews and Nankervis, 1995; Bravard and Petit,  
207 1997; Moog and Whiting, 1998; Pitlick and Cress, 2000; Assani and Petit, 2004; Houbrechts *et al.*, 2006,  
208 2015, Papangelakis, 2013; Phillips, 2015). Only Métivier *et al.* (2017) and Pfeiffer *et al.* (2017) found

209 incipient motion close to bankfull conditions. Pfeiffer *et al.* (2017) demonstrated still that  $\tau_{*c}$  was about  
210 2.35 times lower in the West coast rivers (USA) because of surface armoring. Petit *et al.* (2005) gave  
211 several examples of bedload mobilization around  $0.7 Q_{bf}$  in gravel bed streams similar in size, slope and  
212 substrate to those of the Morvan. Accordingly, we chose to consider a unique theoretical critical  
213 discharge of  $0.7 Q_{bf}$ . This choice was also guided by a few direct additional observations made during  
214 gauging campaigns of several of our sites indicating that the bed material began to move for discharges  
215 ranging from 0.5 to  $0.7 Q_{bf}$ . Although the critical discharge may not equate exactly to  $0.7 Q_{bf}$  for all of  
216 our sites, this approach enables a consistency of the error between the sites.

### 217 **3.2 Morphological data and grain size distribution**

218 Longitudinal profiles and the cross sectional geometry of the study sites were surveyed with a Trimble  
219 total station S6. At least 13 cross sections spaced by 1.5 times the bankfull width were made on each  
220 site. These topographical surveys were then used to calculate the bed slope and build a DEM on GIS  
221 (Arcgis software), which was then loaded into HEC-RAS software (section 3.1). The grain size  
222 distribution of the riverbed was determined using Wolman's surface sampling method (1954). We tried  
223 to respect a sampling step equating to twice the b-axis of the largest particle of the sampled unit (Lejot,  
224 2008; Belliard *et al.*, 2009). Three sub-reaches were delimited along the study reach as a function of  
225 their apparent geomorphological homogeneity (bankfull width and depth, grain size range, substrate  
226 arrangement) even if geomorphological variations within the same reach were generally very limited.  
227 At least 100 particles per sub-reach were sampled and measured, resulting in a minimum of 300 particles  
228 per site.

### 229 **3.3 Bedload transport monitoring**

230 Bedload transport was studied with Radio Frequency Identification (RFID) technology. Individual  
231 particles were tagged with a Passive Integrated Transponder (PIT) that can be identified by a unique  
232 number thanks to the RFID technology. This is now commonly used for bedload transport studies  
233 (Lamarre *et al.*, 2005; Rollet *et al.*, 2008; Liébault *et al.*, 2012; Bradley and Tucker, 2012; Chapuis *et*  
234 *al.*, 2014; Phillips and Jerolmack, 2014; Houbrecht *et al.*, 2015; Dépret *et al.*, 2017). The technique  
235 presents numerous advantages and a series of limits well described by Piegay *et al.* (2016). Among the

236 benefits of the technique, are the fact that the tracers are not disturbed between detections, as well as the  
237 relatively low cost and the long lifetime of the tag. With regard to limitations, one may mention that this  
238 is a time consuming method, there is an initial modification of the bed structure when sampling the bed,  
239 and the PIT tags cannot be detected when buried under a range of sediment depth values varying between  
240 20 cm (Houbrechts, 2012), 45 cm (Chapuis *et al.*, 2014) and 70-89 cm (Arnaud *et al.*, 2015), for the  
241 “small” circular antennas that we used. During our field surveys, in the few instances when it was  
242 possible to test this detection range, it appeared that tracers were hard to detect beyond 25 cm of burial  
243 depth.

244 In this study, 50 tagged particles (tracers) were first injected at each site between August and October  
245 2014 (Table 2). At the study sites with active bedload transport, some initial tracers may rapidly have  
246 been able to go farther than the prospected area. 25 additional tracers were then injected in October  
247 2015. The particles to tag were selected in the riverbed using the Wolman coarse grain sampling method  
248 (1954). However, the tracers’ size range does not completely follow grain size distribution of the bed  
249 because the tags we used were 32 or 23 mm long. Consequently, no particle with a b-axis under 20 mm  
250 was tagged. Also, for logistical reasons we were not able to tag more than few particles per site with a  
251 b-axis above 130 mm. This led to a slight discrepancy between the  $D_{50}$  injected and the  $D_{50}$  of the bed,  
252 that is accentuated with the  $D_{84}$  percentile (Table 2). On sites with the largest grain size, this could have  
253 led to a slight overestimation of the mean distance travelled by the tracers over the potential mean  
254 distance travelled by the “unmonitored” bedload. This possible overestimation of the travel distance is  
255 discussed in section 5.5.

256 Tracers were injected along the cross sections at an interval of 1.25 m. Each cross section was separated  
257 by at least 2 m. Surveys of the tracers’ positions were undertaken between November 2014 and April  
258 2017 with a round, 0.55 m-diameter antenna. The distances travelled by the marked particles were  
259 measured using a flexible ruler (tape measure) unrolled along the bank. Due to the degree of precision  
260 of the measurements (antenna radius: 0.5 m), tracers were considered as mobile when they had moved  
261 forward at least 0.6 m beyond their previous known position for the first 80 m of the study sites. Beyond  
262 80 m, we considered mobilization if the tracers moved more than 1 m. This increase in error margin is

263 based on the observation that beyond a 75-85 m length, noticeable disparities (from 0.02 m to 0.06 m)  
264 in the ruler roll-out between two surveys can appear owing to irregularities along the bank (trees,  
265 boulders).

266 Except if mentioned otherwise, the displacements recorded during the first survey after injection are not  
267 displayed in the results below. Even if tracers were carefully inserted within the alluvial substrate, by  
268 excluding the displacements recorded during the first survey we aim to prevent any “artificial”  
269 protrusion effect favoring tracers’ mobility (Bright, 2014; Houbrechts *et al*, 2015; Olinde and Johnson,  
270 2015).

271 In addition, we paid attention to only compare the monitoring results of tracers obtained with equally  
272 good surveying flow conditions: i.e. when the water level and flow strength were low enough to prospect  
273 more than 90 % of the reach area (except for the specific S6 site, where a section of the fluvial reach  
274 between 120 and 160 m length is permanently hard to access because of water depth and slippery  
275 substrate). In the end, except when cumulative distances are discussed in section 4.1, the bedload data  
276 presented in this paper come from three surveys realized on each of the Yonne sites (S6, S7, S8), four  
277 surveys on the Chalaux (S5) and S3 Cure sites, and five surveys on the S2 Cure site.

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286 **Table 2. Details of the injected PIT tag tracers**  
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Site and river	S2- Cure	S3- Cure	S5- Chaloux	S6- Yonne	S7- Yonne	S8- Yonne
<b>Injection date (50 first tracers)</b>	15/08/14	16/08/14	29/09/14	30/10/14	31/10/14	31/10/14
<b>Last survey date (duration in years)</b>	18/04/17 (2.7)	20/04/17 (2.7)	22/04/17 (2.6)	22/03/17 (2.4)	24/03/17 (2.4)	23/04/17 (2.5)
<b>Total number of tracers</b>	75	50	75	75	75	75
<b>D<sub>50</sub> injected tracers (mm)</b>	63	60	62	58	58	63.5
<b>D<sub>50</sub> injected tra- cers / D<sub>50</sub> riverbed</b>	0.47	0.23	0.78	0.78	0.55	0.76
<b>D<sub>16</sub> injected tra- cers / D<sub>16</sub> riverbed</b>	0.88	0.97	1.86	0.97	1.02	1.13
<b>D<sub>84</sub> injected tra- cers / D<sub>84</sub> riverbed</b>	0.50	0.13	0.68	0.79	0.37	0.55

288

## 289 **4. Results**

### 290 **4.1 Relationship between bedload distances and river energy**

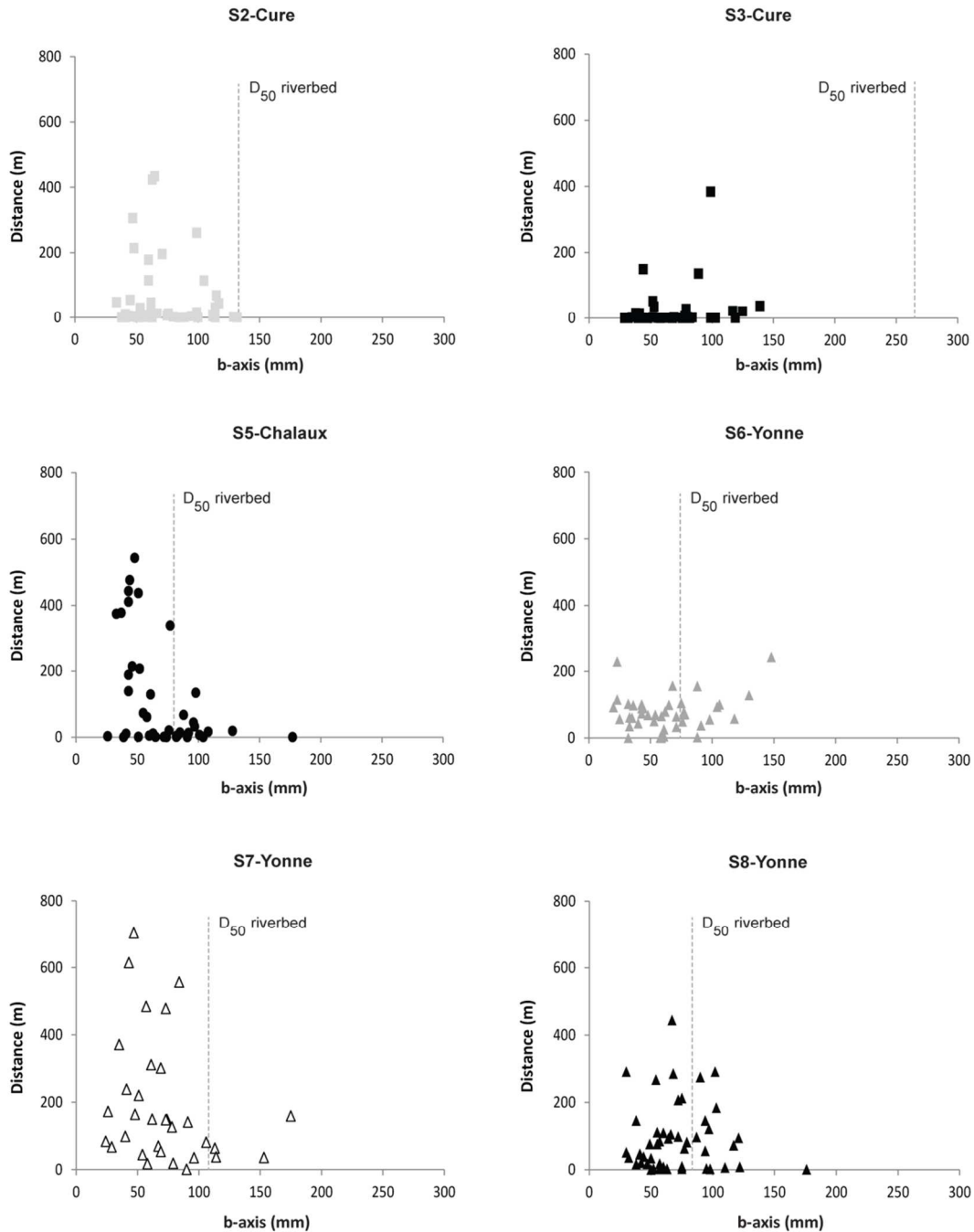
291 Fig. 4 and Table 3 give a first overview of the cumulative bedload transport observed at each site about  
 292 2.5 years after the injection of the first tracers. One may first notice a different intensity according to the  
 293 rivers: the Yonne and the Chaloux appear to be rather dynamic systems (in terms of distance travelled  
 294 and mobilization rates), while the Cure presents lower bedload transport activity. A distinction may  
 295 however be made between the S2 Cure site and the S3 Cure site. S2 presents medium transport activity  
 296 but a mean travel distance close to the S6 Yonne site, while the S3 site shows a noticeably low transport  
 297 activity. At all of the study sites considered, the mean distance travelled by the tracers varies between  
 298 24 m to 315 m over about 2.5 years (the cumulative travel distances at S6 are probably underestimated  
 299 as mobile tracers located in the previously mentioned “hard to survey” sub-reach, between 120 and 160  
 300 m, are not taken into account). If we exclude S6, the largest particles injected have not been significantly  
 301 transported (or not transported at all) and sediment sorting has clearly developed on sites S2, S5, S7 and,  
 302 in a less obvious way, on S8. In Table 3, the D<sub>50</sub> of the mobilized tracers is close to or slightly under the



303 median size of all detected tracers (i.e.  $D_{50}$  tracers, which does not exactly equate to the injected tracers'  
304  $D_{50}$  from Table 2) and is therefore still much smaller than the  $D_{50}$  of the bed (Table 1).

305

306



307

308 **Fig. 4. Relationship between cumulative bedload distances and the median diameter of tracers**  
309 Distances are based on the results of the last monitoring survey only.

310

311 **Table 3. Cumulative data on bedload transport in Morvan rivers**  
 312

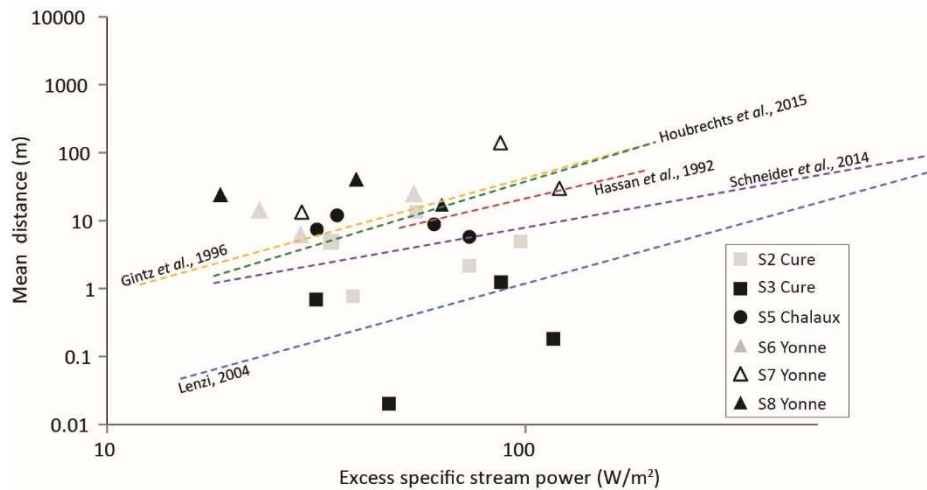
Site and river	S2- Cure	S3- Cure	S5- Chaloux	S6- Yonne	S7- Yonne	S8- Yonne
Mean distance (m)	67.5	24	141	78	315	123
D <sub>imax</sub> mobilized (mm)	144	139	128	148	175	122
D <sub>50</sub> tracers (mm)	62.5	59	73	69.5	61	75
D <sub>50</sub> mobilized tracers (mm)	63	65.5	58	61	58	68
Mobilization rate	0.69	0.50	0.80	0.91	0.97	0.94

313 Distance values are based on the results of the last monitoring survey only and the mean values include tracers that  
 314 did not move. The D<sub>50</sub> tracers represents the median grain size of the detected tracers, including tracers that did  
 315 not move. D<sub>50</sub> mobilized tracers include only mobile tracers.

#### 316 **4.1.1 Excess stream power and duration of the competent flow**

317 The excess stream power of the highest peak discharge between two PIT tag surveys is compared in Fig.  
 318 5 to the mean distances travelled during this same period. Though the data set of our 6 study sites is  
 319 rather coherent with observations from the literature (Hassan *et al.*, 1992; Gintz *et al.*, 1996; Lenzi,  
 320 2004; Schneider *et al.*, 2014; Houbrechts *et al.*, 2015), no evident relationships appear and the data  
 321 presents a large scatter around the literature relationships. This large dispersion of the data first reflects  
 322 a certain diversity of functioning between the different sites despite the apparent homogeneity of the  
 323 rivers studied. This suggests that the inner diversity of the sites (slope, channel geometry, roughness and  
 324 structure of the bed) has to be explored in detail. The Cure river experienced much shorter displacement  
 325 than the other river reaches. Yet S3 is the study site presenting the steepest slope (0,015 m/m), the largest  
 326 D<sub>50</sub> (26.5 cm) and the highest D<sub>84</sub>/D<sub>16</sub> ratio (17.17) (Table 1). The potential influence of high bed  
 327 roughness on the displacement of particles should be investigated further.

328



329

330 **Fig. 5. Relationship between the mean inter-survey distance (0 values included) and the maximal**  
 331 **inter-survey excess specific stream power.**

332 Indeed another notable issue appears from the Fig. 5. There is a very poor relationship between excess  
 333 stream power and the corresponding mean distance (even within the same site). Indeed if a regression  
 334 line were plotted for each site, most of the time the surveys involving the most powerful peak flows  
 335 would never correspond to the longest mean distance travelled. The correlation is even negative in many  
 336 instances, with travel distance relatively shorter for the largest flood events. The magnitude of the  
 337 highest flow peak is in our case not sufficient to describe travel distance.

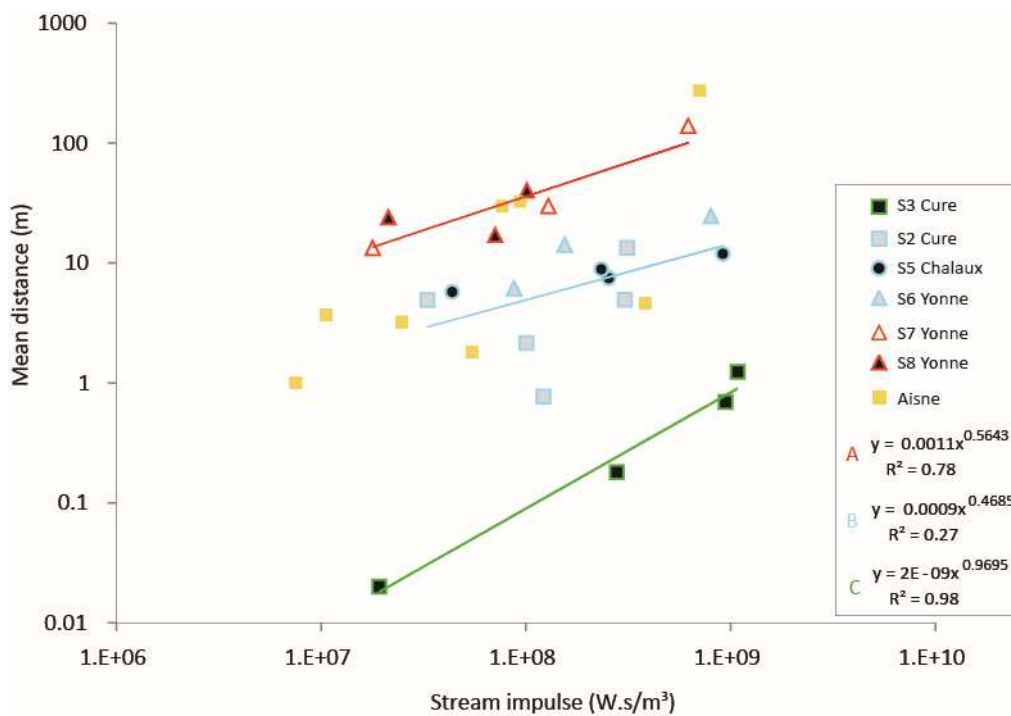
#### 338 4.1.2 Stream impulse

339 In order to combine duration and magnitude of the overall flow over the critical threshold, we considered  
 340 the stream impulse (SI) presented in the Eq. (3). Fig. 6 shows the relationship between SI and the  
 341 corresponding mean distance. It shows that the use of stream impulse is more adapted for the  
 342 understanding of our bedload distance data. Indeed, almost all sites show a clearer positive relationship  
 343 between energy, flow duration and travel distance. Three groups of sites appear now rather clearly. They  
 344 are mainly based on the differences of distance range for a given stream impulse range and they gather  
 345 sites with some common morphological features.

346 The first group concerns the most dynamic sites, S7 and S8 on the Yonne river (regression A,  $R^2 = 0.78$ ,  
 347  $P\text{-value} = 0.018$ ). The second group gathers the observations of S2, S5 and S6 (regression B,  $R^2 = 0.27$ ,  
 348  $P\text{-value} = 0.081$ ). The last one confirms what Figs. 5A and B had already shown: despite similar or higher

349 stream impulse values, the tracers at S3 travel shorter distances than at the other sites (regression C,  $R^2$   
 350  $= 0.98$ ;  $P$ -value=0.01). As already mentioned, S3 is the steepest reach ( $s = 0.015$  m/m) with a stream bed  
 351 that includes a lot of large cobbles ( $D_{50} = 26.5$  cm). Group A is almost as steep ( $s > 0.008$  m/m) but with  
 352 smaller particles ( $D_{50} = 8.3$  and  $10.8$  cm). Meanwhile, group B reaches have lower slopes ( $s < 0.0075$   
 353 m/m) but show a wider range of median grain size ( $7.4 < D_{50} < 13.3$  cm). This group may be slightly less  
 354 homogeneous morphologically (e.g. bankfull width, Table 1). On Fig. 6, the dots from group B are also  
 355 a bit more scattered (S2 especially) and this explains the low coefficient of determination and their  
 356 statistical non-significance according to  $P$ -value calculation.

357



358

359 **Fig. 6. Relationship between the mean travel distance and the stream impulse (SI).** Colored  
 360 borders of dots and colored curves highlight the three groups (A, B, C) that have been distinguished.

361 Data used by Houbrechts *et al.* (2015) on the Aisne river were plotted in Fig. 6 for comparison. This  
 362 river flows in Southern Belgium within a morpho-climatic context quite similar to the Morvan massif.  
 363 The  $D_{50}$  of the bed is  $9.2$  cm, its slope  $0.0053$  m/m and its bankfull width  $13.57$  m, and the critical  
 364 discharge for particle entrainment represents  $55\%$  of the bankfull discharge. The correlation between

365 mean distance and stream impulse is also rather obvious for the Aisne data ( $R^2 = 0.53$ ; P-value = 0.04).

366 The Aisne scatter plot shows a trend similar to the Morvan's A and B relationships.

367 Despite "time" and "storage processes" as potential complexity factors on the Aisne river (see

368 Discussion section, 5.2), Fig. 6 shows clearly that using the stream impulse (SI) allows the description

369 of the travel mean distance of the tracers to be greatly improved. Nonetheless, the dispersion of the

370 Morvan data remains quite large and, at this stage, the reasons why still have to be clarified.

#### 371 **4.2 Relationship between bedload distances and morpho-hydraulic parameters**

372 The mean travel distances of tracers has been normalized by different morphological and hydraulic

373 parameters (Fig. 7A-D) in order to identify the reasons behind the discrepancy observed on Fig. 6. The

374 parameters are: relative grain size corresponding to the  $D_{50 \text{ tracers}}/D_{50 \text{ bed}}$  ratio (A), where the first term is

375 the  $D_{50}$  of the tracers whose displacement distance is known, immobile tracers included; bed channel

376 slope (B); relative flow depth (C), given by the ratio between the reach averaged water depth for the

377 peak discharge of the inter-survey period and the  $D_{84}$  of the bed; and reach averaged width/depth ratio

378 for the peak discharge of the inter-survey period (D).

379 In Fig. 7A-D, 3 groups of data can be distinguished again and they are globally the same groups

380 described in Fig. 6. However the gap between the relationships fluctuates following the parameter used

381 for normalization, giving a clearer idea of what and how morpho-hydraulic features may influence

382 bedload travel distance on each study site.

383 The relative grain size is likely to influence S3 travel distances, as can be seen from the normalization

384 in Fig. 7A, which brings S3 closer to the other sites (compared to Fig. 6). The relative grain size of the

385 tracers on this site is by far the lowest (Table 4) and a hiding effect may then contribute to explain the

386 low recorded distances. Compared to Fig. 6, S7 and S8 data are closer to S3 data on Fig. 7A because

387 their tracers have on average a relative grain size that is much higher than the relative size of S3 tracers

388 (Table 4). In S7 and S8, boulders are present but they are less numerous and they are smaller than on

389 S3. S7 and S8's riverbeds are also much better sorted in terms of grain size than S3's riverbed, where a

390 deficit of medium sized particles can be observed (Table 1). The relative grain size may also contribute

391 to the relative scattering of the Group B data for a comparable stream impulse, observed on Fig. 7 as  
392 well as on Fig. 6. S5 and S6 present the highest values whereas S2's mean relative grain size is much  
393 lower (Table 4).

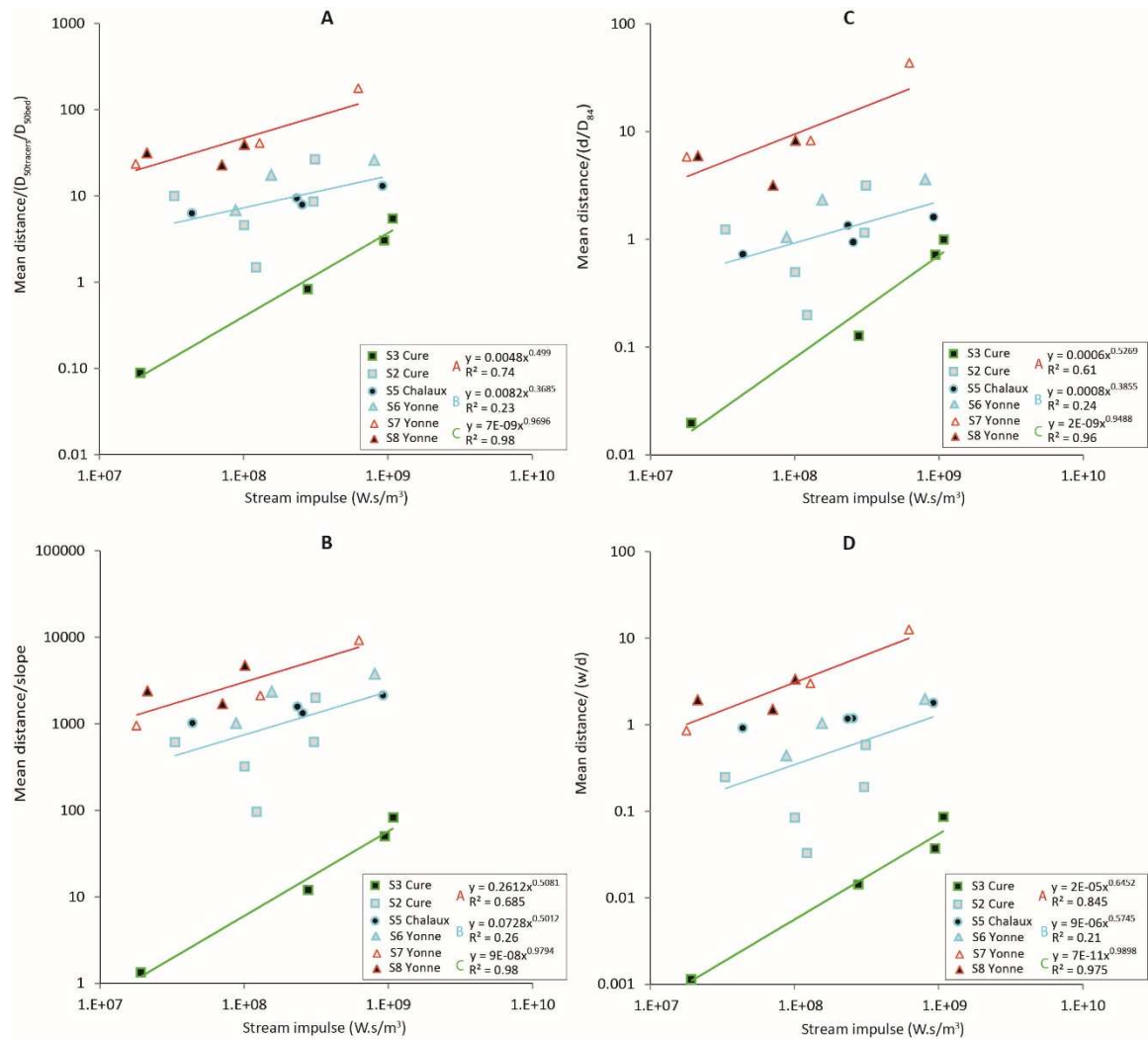
394 The different groups of study sites present a more unclear relationship with the bed slope (Fig. 7B). The  
395 higher bed slope of the A and C groups ( $s \geq 0.008$  m/m, Table 4) increases normalized travel distances  
396 to a lesser degree than for the sites of the intermediary group (S2, S5 and S6) which have lower slopes  
397 ( $s \leq 0.0073$  m/m) (Fig. 7B). S7 and S8 data are then closer to these intermediary sites in Fig. 7B, when  
398 S3 appears even more isolated. A significant slope is therefore associated with short (group C) and long  
399 (group A) bedload travel distances, and a moderate slope corresponds to the group with intermediary  
400 bedload distances (B).

401 The relative flow depth on S3 group C is also shown as a parameter that may contribute to the low travel  
402 distances, as emphasized by its use for normalization that clearly gets S3 data closer to B group (Fig.  
403 7C). The high slope and the presence of boulders on S7 and S8 induces a relative flow depth that is  
404 lower than the intermediary B group (except for S2), increasing the disparity between groups A and B  
405 (Fig. 7C). Thus, a group of data is showing important bedload displacements despite a low relative flow  
406 depth (A) and another shows very short bedload displacements that may be partly explained by a very  
407 low relative flow depth (C). In group B, S2 presents a large  $D_{84}$  leading to a mean relative flow depth  
408 close to S8 and just higher than S7. This is why normalization of mean distances with relative flow depth  
409 does not "move" S2 data as far from S7 and S8 as it does for S5 and S6 (Fig. 7C). Indeed, these have  
410 the highest relative flow depth values because of lower bed slope,  $D_{84}$  and bankfull width values (Table  
411 1 and Table 4). This higher relative flow depth, combined with the higher relative grain size and the  
412 substrate homogeneity on S6 (Table 1, index sorting), are hydro-morphometric features that may  
413 "compensate" the lower bed slope of these sites. This suggests, however, that (increasing) slope as a  
414 parameter fostering bedload transport as on S7 and S8 should be considered. The positive or negative  
415 effect of the bed slope will be further questioned in section 5.4.

416 In group B, for S5, bedload mean distances may also be supported by a very low w/d ratio, compared to  
417 the other sites (Table 4). This may favor increased bedload travel distance as potentially indicating a  
418 higher depth during floods and then a higher shear stress for a given discharge. The normalization with  
419 this parameter (Fig. 7D) clearly brings S5 data closer to S7 and S8. Inversely, the Cure sites have the  
420 highest w/d ratios because of their larger width (S2), or their low flow depth due to bed slope (S3). This  
421 maintains S3 normalized distances beneath the other sites' values and lowers S2 data. These even tend  
422 to separate from other data of the B intermediary group (Fig. 7D), underlining once again the link  
423 between different morpho-hydraulic parameters and scattered bedload distances within this group itself.

424

425



426

427 **Fig. 7. Relationship between mean travel distance normalized by hydro-morphometric**  
 428 **parameters and stream impulse (SI). A) Mean travel distance normalized by relative grain size,**  
 429 **B) Mean travel distance normalized by the bed slope, C) Mean travel distance normalized by**  
 430 **relative flow depth, D) Mean travel distance normalized by the width/depth ratio. Equations**  
 431 **correspond to the best-fit relationship.**

432

433 **Table 4. Mean values of the morpho-hydraulic parameters**

Site and river	S2- Cure	S3- Cure	S5- Chalaux	S6- Yonne	S7- Yonne	S8- Yonne
Mean* relative grain size of the tracers	0.51	0.23	0.93	0.88	0.69	0.84
Bed slope (m/m)	0.007	0.015	0.0056	0.0073	0.0015	0.0085
Mean* relative flow depth	4.14	1.14	7.43	6.25	3.03	4.76
Mean* Width/depth ratio	23.5	17.2	6.7	13.3	12.1	11.8

434 \*Corresponding to the mean value of the different RFID surveys or inter-survey periods.



435 **4.3 Stepwise multiple linear regression**

436 Simple bivariate regressions of Fig. 7 allowed parameters that discriminate mean travel distance to be  
 437 identified. However, in order to quantify the degree of influence of each parameter and propose a single  
 438 relationship allowing mean distance to be predicted, stepwise multiple linear regression was tested. The  
 439 five parameters tested were chosen according to the results of the bivariate relationships presented  
 440 above: stream impulse (SI), relative grain size ( $D_{50\text{tracers}}/D_{50\text{bed}}$ ), relative flow depth ( $d/D_{84}$ ), bed channel  
 441 slope (s) and width/depth ratio (w/d). Only three of them were finally defined as having a significant  
 442 influence during the analysis (Table 5), allowing the following prediction model to be proposed:

$$\bar{L} = \text{EXP} (7.3805 + 0.4069 \text{LN} (\text{SI}) + 3,8896 \text{LN} \left( \frac{D_{50\text{tracers}}}{D_{50\text{bed}}} \right) + 2.3694 \text{LN} (\text{S})) \quad (4)$$

443 Where  $\bar{L}$  is the mean bedload distance, SI the stream impulse,  $D_{50}$  tracers is the median grain size of the  
 444 tracer whose displacement distance is known, immobile tracers included, and S is the bed slope. This  
 445 model has a quite convincing adjusted coefficient of multiple determination ( $R^2 = 0.73$ ) with a rather  
 446 good residual standard error of 1.064, P-value <0.001 and F-statistic = 17.43.

447

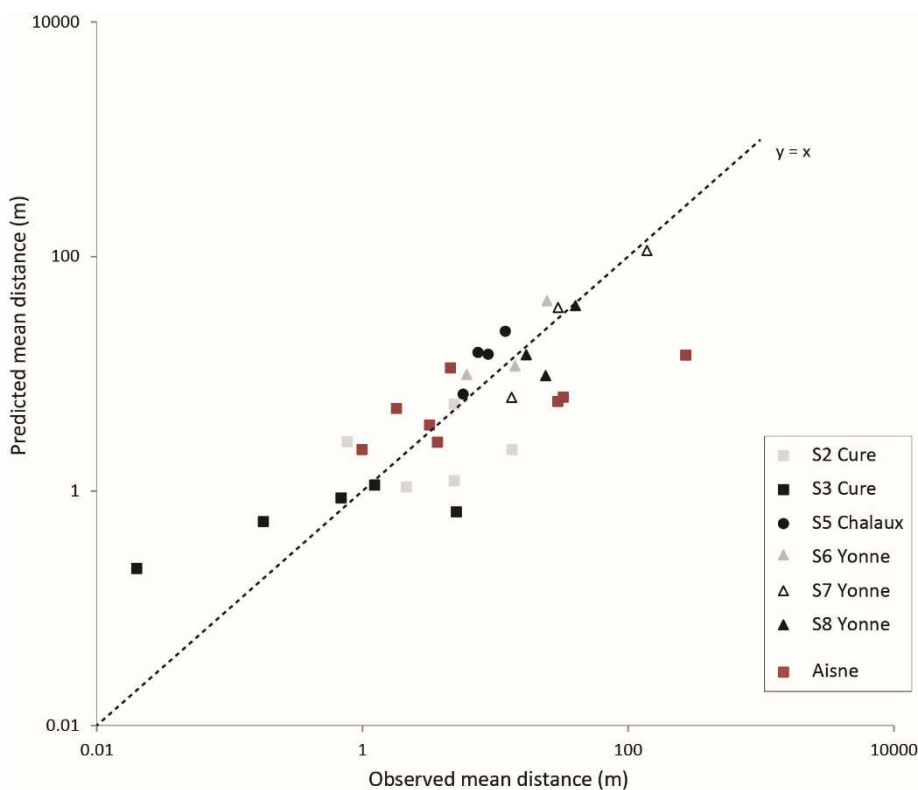
448 **Table 5. Results of the stepwise multiple regression**

	Std. Error	t value	P-value r(> t )	Significance
<b>Intercept</b>	4.8936	1.508	0.14796	**
<b>Log (SI)</b>	0.1804	2.256	0.03606	*
<b>Log (<math>D_{50\text{tracers}}/D_{50\text{bed}}</math>)</b>	0.5771	6.740	1.93e-06	***
<b>Log (s)</b>	0.8055	2.941	0.00838	**

449

450 The model provides quite strong predictions for most of our study sites. Once again it is the S3 site on  
 451 the Cure that diverges most from the other study sites. In this case, our model poorly predicts two S3  
 452 surveys with a clear overestimation of the low tracer displacement (Fig. 8). A test was also realized with  
 453 the Aisne river data (Houbrechts *et al.*, 2015). These were not included in the multiple regression

454 analysis that enabled to build the Eq. (4). The test tends to validate the model as we obtain predicted  
455 distances that genuinely match for all but one of the observed distances (Fig. 8).



456

457 **Fig. 8. Comparison between the observed mean distance of tracers and the predicted mean**  
458 **distance from Eq. (4).**

459 When looking at Fig. 8 in more detail, one may notice a slight offset of certain data towards the bottom  
460 of the graph (i.e.) indicating an underestimation of the predicted distance. This concerned notably the  
461 three largest mean distances observed on the Aisne river. These three largest mean observed distances  
462 on which this underestimation applies were also recorded for three of the four inter-survey periods with  
463 the highest stream impulse. A possible underestimation of the stream impulse for high flow events is  
464 discussed in the section 5.2.

## 465 5. Discussion

### 466 5.1 Bedload dynamics poorly explained by the commonly used hydraulic parameters

467 Bedload travel distances recorded on Morvan rivers are very different according to the study sites (Table  
468 3 and Fig. 4). Also, for the same site, the travel distance appear moderately correlated with the higher  
469 flood peak (Fig. 5A). The longest displacements are rarely coupled with the greatest excess stream

470 power. Conversely, in many instances, the largest events correspond to shorter displacements. This is  
471 quite counterintuitive and diverges from what the literature has repeatedly shown (Hassan *et al.*, 1992;  
472 Gintz *et al.*, 1996; Lenzi, 2004; Schneider *et al.*, 2014; Houbrechts *et al.*, 2015).

473 Comparisons with the literature may bring precious information but should be used with caution because  
474 of the differences in methodology (first peak or maximal peak discharge considered, tracer replacement,  
475 number of flood peaks considered) that may lead to very divergent results. Indeed, Fig. 5 shows that our  
476 results do not entirely match with data from the literature. Moreover, while the Morvan data has been  
477 acquired only in plane-bed channels, the data from the literature presents a dispersion corresponding to  
478 results from a wide range of bed morphologies: from other plane-beds (Houbrechts *et al.*, 2015) to  
479 riffle-pools (Hassan *et al.*, 1992; Houbrechts *et al.*, 2015) and even step-pools (Gintz *et al.*, 1996; Lenzi,  
480 2004; Schneider *et al.*, 2014).

481 The high rate of displacement related to a short inter-survey period observed in our data set for two  
482 surveys (S7 and S8) is a good example of this methodological question. They present high distances for  
483 a relatively low competent flow duration and low excess stream power peak because of the short period  
484 we left between the previous surveys (65 days for S7 and 69 days for S8). Long distance traveled may  
485 then have been stimulated by tracers not well inserted in the bed structure and by transport mostly  
486 operated during the first hours (or the first event) of the competent flow. These elements echo a recent  
487 study from Dell’Agnese *et al.* (2015) underlining the influence of different flow competent durations on  
488 bedload virtual velocity through the capacity to get closer to the actual virtual velocity.

489 The weak correlation between bedload displacements and the maximal excess stream power of our data  
490 may also be explained by the way the excess stream power is calculated (Fig. 5). Indeed, only the highest  
491 peak discharges of the inter-survey periods are considered. Meanwhile, each of these periods  
492 encompasses several flood peaks of variable magnitude and duration. This, therefore, should lead to  
493 noticeable differences with results from “one-peak survey” studies such as those of Gintz *et al.* (1996)  
494 or Houbrechts *et al.* (2015). With this in mind, considering only the magnitude of the highest peak is  
495 clearly not adequate to describe our bedload displacements. The multi-peak characteristics of our

496 surveys forced us to explore the role played by the combination of the magnitude of the high flows and  
497 their duration, as suggested by Papangelakis and Hassan (2016) amongst others.

## 498 **5.2 Relevance of the stream impulse in a multi-peak survey**

499 Inspired by the dimensionless impulse developed by Phillips and Jerolmack (2014) and echoing the  
500 excess energy expenditure used by Haschenburger (2013) and Schneider *et al.* (2014), the stream  
501 impulse (SI) enables the flow competence duration and the overall excess stream power to be integrated.

502 On Morvan rivers, the bedload mean distance is clearly better correlated with the stream impulse than  
503 with the sole magnitude of the largest peak flow, especially when grouping the data according to the  
504 riverbed characteristics (Fig. 7). This should, however, be considered with some nuances as some of  
505 these relationships are built on a limited number of dots.

506 The introduction of independent data from the Aisne river, confirms the relevance of using the stream  
507 impulse to characterize the flows. However, the Aisne river data also brings forward the potential  
508 influence of time and burial phenomenon (Ferguson and Hoey, 2002; Haschenburger, 2011; Houbrecht  
509 *et al.*, 2015). Indeed, the two lowest dots of the Aisne data on Fig. 6 have been surveyed 5.5 and 6.3  
510 years after the initial injection of tracers, when the other monitoring surveys occurred within 3.3 years  
511 following the injection, and following a 10-year flood event. This indicates that major events as well as  
512 simple elapsed time since injection have probably contributed to vertical mixing and burial of a part of  
513 the tracers, making them less easy to entrain and thus reducing the distance travelled. This leads us to  
514 emphasize that our study has been realized for a limited duration (about 2.5 years) and to question if the  
515 good correlation between travel distance and stream impulse would be maintained on a longer time  
516 scale.

517 The relationship resulting from the stepwise multiple regression (Eq. (4)) also confirms the interest in  
518 considering stream impulse to predict the mean distance travelled by the particles. The calculation of  
519 the mean distances on the Aisne with this relationship is also rather good except for predictions of  
520 distances corresponding to large flow events (Fig. 8). This results in an underestimation of the distance,  
521 probably because of the different resolutions in the hydrological data. The Aisne instantaneous discharge

522 data (used to calculate the SI) are indeed measured every hour whereas the Morvan data are measured  
523 every 15 minutes. It is then possible that the highest peak discharges, and consequently the maximum  
524 excess stream powers were less precisely recorded for the Aisne river.

### 525 **5.3 The dominant influence of relative grain size: meanings and trails to explore**

526 Our study supports the idea that bed sorting and grain size range distribution greatly affect sediment  
527 transport. The site with the lowest mobility (S3) is also the site with the poorest bed sorting (Table 1).  
528 Previous studies indicate that a low relative grain size can increase the critical threshold for sediment  
529 mobilization (Mao *et al.*, 2008; Gob *et al.*, 2010; Parker *et al.*, 2011). Our work shows that it may also  
530 affect bedload transport by limiting the travel distance. This effect may be seen as the result of higher  
531 critical conditions: (i) for sediment entrainment, delaying sediment departure; (ii) for sediment transport  
532 itself, with coarse grains that stand in the way or increase flow resistance, then reducing sediment step  
533 length.

534 The dominant influence of relative grain size on bedload tracer distances may have implications on the  
535 type of bedload mobility occurring in Morvan rivers. Indeed, the hidden / exposure effect due to relative  
536 grain size is likely to foster selective mobility and even an equal mobility in the stream beds where  
537 sediment motion is the most determined by relative grain size (Robert, 1993, 2003; Wohl, 2014). Equal  
538 mobility due to the presence of large particles on the bed has been notably underlined by Klösch and  
539 Habersack (2018) on the Puerto Rican Mameyes river (data from Phillips *et al.*, 2013), which has a  
540 similar morphology to the Morvan rivers. The low bedload tracer distances on the S3 site could then  
541 come from the quasi absence of movement of coarse particles that hide the smaller ones and foster the  
542 formation of pebble clusters and other imbricated structures. The question of the current competence of  
543 the river and its ability to entrain these very coarse grains is therefore essential for the general mobility  
544 of all gravel fractions.

545 Conditions around equal mobility is all the more likely to occur when there is a deficit of the medium  
546 grain size fraction and a more or less well-formed armored layer (Parker and Klingeman, 1982). On the  
547 S3 Cure site, one may notice a highly stable interlocked configuration around large grains but not really

548 the mobile armor in the surface layer that is often associated with equal mobility (Parker and Klingeman,  
549 1982). In fact, the bed of the Cure on the S3 reach corresponds to a static armor (Sutherland, 1987;  
550 Parker and Sutherland, 1990). This is also why conditions of equal mobility are partial on the S3 Cure  
551 site: critical conditions for erosion and transport, and entrainment resistance are heightened for medium  
552 and small grain size fractions (low relative grain size, and potential imbrication) but they seem to remain  
553 very high for coarse, apparently immobile, cobbles and boulders.

554 Big particles are also present on the S7 Yonne river site but they lay among a considerable amount of  
555 medium grain size fractions (see sorting index in Table 1). This lower heterogeneity of the substrate and  
556 the lower relative grain size explain the differences of mean distances regarding S3, especially with  
557 stream impulse values and slope that are comparable and quite close on both sites. In the S7 morpho-  
558 sedimentary configuration, the sheltering effect of coarse cobbles and boulders also exists but influences  
559 the displacement of smaller particles to a lesser degree.

560 The dominant influence of the relative grain size on bedload distances underlines the influence of micro  
561 bed topography, especially in plane-bed rivers with heterogeneous grain size distribution. Indeed, in the  
562 absence of medium or large-scale bedforms consuming the river's energy (meanders, alluvial bars, step-  
563 pool or riffle-pool sequences, etc.) (Petit *et al.* 2005), the role of the surrounding particles in the  
564 entrainment resistance of a given particle (sheltering / protrusion effect) is all the more important. This  
565 also invites us to examine more deeply the influence on bedload distances of small-scale characteristics  
566 other than relative grain size, such as imbrication degree, micro-scale bed forms (e.g. pebble clusters)  
567 and grain scale flow resistance (Robert, 1990; 2003; Lamb *et al.*, 2017) in the context of plane-bed  
568 morphology.

#### 569 **5.4 The complex influence of the slope on bedload mean distances**

570 The bed slope is the second most significant parameter influencing mean bedload distance according to  
571 our multivariate analysis. The first reason is of course that slope conditions the energy of the river. The  
572 second reason is less obvious, it is because slope may increase flow resistance by favoring a low relative  
573 flow depth (Bathurst, 2002; Lamb *et al.*, 2008; Parker *et al.*, 2011; Lamb *et al.*, 2017). This leads to a

574 decrease of the transport rate and/or an increase in critical conditions (Miyuzama, 1977; Shvidchenko  
575 and Pender, 2000; Mao *et al.* 2008; Chiari *et al.*, 2010; Parker *et al.* 2011; Prancevic and Lamb, 2015;  
576 Bunte *et al.*, 2013; Lamb *et al.*, 2017). A low relative flow depth may also lower transport activity by  
577 reducing the intensity of turbulent fluctuations (Sumer *et al.*, 2003; Lamb *et al.*, 2017). All these  
578 elements are partly supported by our study in which bedload distances appear positively correlated to  
579 relative flow depth (Fig. 7C). However, from our multivariate analysis it emerged the relative flow depth  
580 was an insignificant explanatory variable despite its evident link with the slope.

581 For the S5 and S3 study sites, slope appears to be negatively correlated to bedload distances. S3 has the  
582 highest bed slope (with S7) but the shortest mean distance (for comparable SI) (Tables 1 and 3; Fig. 6).  
583 On the other hand, S5 distances are in the high range of intermediary distances while having the lowest  
584 slope (Tables 1 and 3; Fig. 6). Several studies already emphasized the positive relationship between  
585 slope and critical shear stress (Mizuyama, 1977; Mueller *et al.*, 2005; Lamb *et al.*, 2008; Gob *et al.* 2010;  
586 Parker *et al.*, 2011). The negative correlation between slope and bedload distances we observe on several  
587 of our sites is therefore not totally unexpected. Slope may lower bedload distances when its effect is  
588 dominated by an increased flow resistance and energy loss. As for relative grain size, these “negative  
589 effects” of slope may diminish bedload distances in two ways: they may heighten critical conditions for  
590 sediment entrainment and then delay their incipient motion for a flood event or reduce the frequency of  
591 mobilization; they may also lead the mobilized particles to settle faster and then reduce the displacement  
592 length.

593 Among the three sites with the steepest slopes (S3, S7, S8), two (S7 and S8) have logically the longest  
594 mean distances (for a comparable SI) (Table 1 and 3; Fig. 6). They also have a higher relative depth and  
595 relative grain size compared to S3. This is also true for the three remaining sites (S2, S5 and S6) with a  
596 lower slope and lower intermediary mean distances. In line with S2, S6, S7 and S8 data, travel distance  
597 tends to increase with channel slope. These observations suggest that slope acts positively on bedload  
598 transport as long as relative depth and relative grain size remain above a certain threshold (in our case  
599  $\approx 2.5$  and  $0.50$  respectively).

600 The S5 Chalaux site differs slightly from this trend: globally it presents comparable or higher distances  
601 than the S2 Cure site and the S6 Yonne site, with the highest relative depth and relative grain size, but  
602 with the lowest slope (Table 1 and 3; Fig. 6). It is also the site with the lowest w/d ratio, even if the direct  
603 influence of this parameter on bedload transport was not recognized as significant. These elements imply  
604 that the impact of slope on transport may be a function of its combination with other parameters such as  
605 flow depth, determined by discharge, flow velocity and river geometry, grain size distribution of the  
606 river bed, *etc.* It may also suggest that if slope may heighten critical conditions for sediment entrainment  
607 (Mizuyama, 1977; Lamb *et al.*, 2008; Gob *et al.* 2010; Parker *et al.*, 2011), in some situations (S7 and  
608 S8), it may increase sediment displacement length once particles are put in motion. The seemingly  
609 ambivalent role of slope on Morvan rivers calls to mind the observation of Prancevic and Lamb (2015)  
610 of the absence of a universal trend in the relationship between critical dimensionless shear stress and  
611 channel slope.

## 612 **5.5 Validity of the model equation and methodological choices**

613 The different results presented in this paper have been, for the most part, statistically valid and the model  
614 equation (Eq. (4)) obtained from the multiple linear regressions have been convincingly validated by the  
615 independent data set of the Aisne river. The margin of error associated with bedload displacement (0.6  
616 to 1m, due to the precision of the RFID Antenna and the precision of our methodology to survey the  
617 tagged particles) may be considered as quite low. Indeed, mean travel distance per inter-survey period  
618 is 16.3 m (immobile tracers included). The error associated with the marked particle location represents  
619 therefore only 4 to 6 % of the distance travelled.

620 Several choices that have been made in this paper could have led to uncertainties that may call into  
621 question our results and, therefore, require further discussion.

622 The first of these choices concerns the threshold for sediment incipient motion. Unfortunately, it was  
623 not possible to determine this precisely from our RFID surveys. Yet the critical discharge is a key  
624 parameter for the calculation of stream impulse or excess stream power. Our choice to consider a  
625 threshold that equals  $0.7 \cdot Q_{bf}$  is therefore a strong assumption that has been widely discussed in the



626 methods section. In the end, our results show that our choice was probably quite accurate, especially  
627 since Eq. (4) has provided very good estimations of travel distance for the independent data of the Aisne  
628 river, for which the incipient motion threshold has been determined empirically on the field. Having said  
629 that, further investigations on the exact critical discharge would be worthwhile.

630 The second of our methodological choices that could have led to a certain level of uncertainty concerns  
631 the size of the largest particles tagged. Indeed, because of our tagging protocol, the coarsest particles of  
632 the riverbed ( $> 175$  mm) were not tagged. This may have induced an underestimation of the maximum  
633 competence of the river. However, we think that these large cobbles and blocks that have not been  
634 marked are in fact immobile. Firstly, the largest particles we tagged did not moved or barely moved  
635 (Table 3 and Fig. 4). Secondly, several indications such as moss, black biofilm, stable imbrication, *etc.*  
636 show that the largest cobbles and the boulders present in the bed should not be considered as bedload  
637 under the current hydrological conditions.

## 638 **6. Conclusions**

639

640 The bedload transport of Morvan rivers is complex and depends on a range of parameters. The multi-  
641 peak characteristic of our surveys requires the integration of every discharge over the critical threshold,  
642 in terms of intensity and duration, and not only the highest peak, in order to evaluate the hydrological  
643 influence on bedload travel distances. The time integrated energy parameter we use – stream impulse –  
644 enables us to give more meaning to our data. However, it is not sufficient to fully understand the recorded  
645 differences of bedload displacements as the dispersion of tracer distances draws three distinct  
646 relationships. Also, when plotted with a classical energy indicator (excess specific stream power),  
647 bedload displacements cover a wide range of values obtained from other studies on different channel  
648 morphological types (plane-bed, riffle-pool, step-pool). This variability of distance values leads us to  
649 investigate the influence of more specific morphological and hydraulic parameters (and the role of their  
650 own variability) on bedload transport in a plane-bed context. The stream impulse and the other four  
651 hydro-morphometric parameters that we tested (relative grain size, relative flow depth, slope, w/d ratio)  
652 bring us useful information to highlight what controls bedload transport on Morvan rivers. The multiple

653 regression analysis indicates that the relative grain size, the slope and the stream impulse are, in order  
654 of significance, the most important parameters influencing bedload distances.

655 Relative grain size, the first controlling factor on bedload mean distance on Morvan rivers, emphasizes  
656 the importance of microtopography and grain size distribution range in plane-bed rivers. Substrate  
657 arrangement and very coarse particles compose various grain/micro to medium scale features. These are  
658 probably even more important to consider in this plane-bed channel morphology as they represent the  
659 main constraints to particle entrainment (hiding effect, imbrication, stable sedimentary structures) and  
660 the main sources of flow resistance (immobile cobbles and boulders, transverse ribs, clusters).

661 The role of the slope has already been studied in relation to critical conditions for incipient motion. Our  
662 study shows that it significantly affects direct bedload distances. The way in which bed slope has an  
663 influence is ambiguous though, and seems to depend on other hydro-morphometric factors: it notably  
664 appears to act in favor of bedload travel distances when the coarsest particles are largely submerged  
665 ( $d/D_{84} > 2.5$  at least). Nonetheless, the multiple regression suggests that slope impacts bedload distances  
666 more significantly in other ways.

667 The single model equation we obtained to predict mean bedload distance (Eq. (4)), combining stream  
668 impulse (SI), relative grain size and bed slope, functions pretty well with our own data and with data  
669 from the Aisne river. However, it is wise to pursue these validation tests further, with other data that are  
670 equivalent to ours (data collection method, geomorphological settings). If validity is confirmed, tests  
671 with other morphological types of fluvial systems and in different morpho-climatic contexts will be  
672 needed to determine the application range of the model.

### 673 **Acknowledgments**

674 The authors would like to thank Matthieu Moës and the Agence de l'Eau Seine-Normandie (public water  
675 agency), for financing the research work leading to this paper. We are also very grateful to Jean-René  
676 Malavoi and Electricité de France (EDF) as well as the PIREN Seine for the financial support they  
677 provided for the purchase of research equipment and for fieldwork missions. We extend our sincere  
678 appreciation to Jonathan Touche for his help on the field and Natasha Shields for her assistance in

679 translating. Finally, we would like to thank F. Comiti and the anonymous reviewer for their thoughtful  
680 comments that enabled the quality of the original paper to be greatly improved.

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