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# A multi-spatiotemporal scale strategy to evaluate factors controlling pebble mobility and its interactions with bedforms in a lowland gravel-bed river

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1                    **A multi-spatiotemporal scale strategy to evaluate factors controlling**  
2                    **pebble mobility and its interactions with bedforms in a lowland gravel-bed river**

3  
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15  
16  
17                    **Highlights**

- 18                    • Very low bedload distances for full mobility floods at the event scale
- 19                    • Weak trapping effect of bedload by bars at both event and decadal scales
- 20                    • Bedload distances are lower than counterpart bedforms' distance at the event scale
- 21                    • Bedload velocity varies depending on the year, bedform type or injection method
- 22                    • Tracers' mixing was incomplete 10 years after their injection at the bed surface

27 **Abstract**

28 This paper aims to analyse how and what controls the spatiotemporal variability in bedload mobility in  
29 a low-energy gravel-bed meandering river, with a particular focus on the interactions between bedforms  
30 (bar-riffle-pool units) and bedload transport distance.

31 We first address the influence of pre-existing morphology, especially bars, upon the event  
32 transport distance, and examine to what extent the maintenance of bedforms requires the occurrence of  
33 hydrological events able to move the bedload over distances at least equivalent to the length of two  
34 successive identical geomorphic units. To do that, we tracked the displacement of PIT-tags particles 10  
35 years after their injection and applied bedload formulas to reconstruct the event transport distance for a  
36 32-year-long study period. Our results show that event bedload distances for the bed surface  $D_{50}$  could  
37 not exceed an active channel width, this one being roughly equivalent to 0.3 times the median distance  
38 between riffles and between pools. This has two main implications. First, the trapping effect by bars  
39 would be rare, or perhaps even absent, at the scale of competent events for most particles located at a  
40 distance greater than an active channel width from a bar. Second, because no event is able to transport  
41 bedload over distances at least equal to the length of one riffle-pool unit, the maintenance of bedforms  
42 and bars especially, would arise from successive minor changes.

43 Further, our data revealed important variability in the bedload velocity at a decadal scale  
44 according to the year of injection, the type of geomorphic unit of injection or the method of injection  
45 (i.e., cluster or cross-section). This highlights the long-term persistence effects in low-energy rivers  
46 upon velocity estimation from where, when and how tracers are injected.

47 Lastly, we inferred the long-term bedload velocity from the PIT-tags data and applied bedload  
48 formulas. Equal to  $0.95\text{--}1.3 \text{ km century}^{-1}$ , it is nevertheless considered an overestimate because the  
49 slowdown of tracers seeded at the bed surface, due to their progressive mixing in the active layer and  
50 their trapping in bars, was still on-going.

51

52 **Keywords:** Tracer dispersion; bedload path length; low-energy meanders; geomorphic units; active  
53 layer

54

## 55 **1. Introduction**

56 In coarse-bed rivers, the bedload is generally considered responsible for shaping much of the fluvial  
57 landscape (Andrews and Nankervis, 1995; Knighton, 1998; Leopold, 1992; Whiting et al., 1999).  
58 Identifying and characterising the modalities of bedload incipient motion, displacements, and deposits  
59 is therefore essential to improve our understanding of the conditions under which morphogenesis occurs.  
60 Bedload movements are generally viewed as stochastic processes (Bradley and Tucker, 2012; Einstein,  
61 1937; Paintal, 1971; Roseberry et al., 2012), these mainly controlled by three groups of parameters:  
62 hydraulic and hydrological characteristics of the entrainment events, structural characteristics of the  
63 sediments, and finally, their textural characteristics (Gilet et al., 2020; Hassan et al., 1991; Hassan and  
64 Church, 1992; Vázquez-Tarrío and Batalla, 2019). Yet the distance travelled by the bedload during a  
65 competent event does not always depend on stochastic processes alone (Pyrce and Ashmore, 2003a,  
66 2003b). In addition to being influenced by the recent flow history and/or sediment supply (e.g.  
67 Buffington and Montgomery, 1999; Church et al., 1998; Dietrich et al., 1989; Downs and Soar, 2021;  
68 Hassan and Church, 2001; Hassan et al., 2020; Haynes and Pender, 2007; Konrad et al., 2002; Lisle et  
69 al., 1993, 2000; Mao, 2012; Masteller et al., 2019; May and Prior, 2014; Monteith and Pender, 2005;  
70 Nelson et al., 2009; Ockelford and Haynes, 2013; Paphitis and Collins, 2005; Reid et al., 1985), both  
71 bed mobility and bedload distance could also be governed and constrained by a bed's morphology; i.e.,  
72 its organization in well-structured geomorphic units, or bedforms. Accordingly, many researchers have  
73 hypothesized that event transport distances scale with certain metrics that characterize bed morphology.  
74 These are considered equivalent to the distance between an erosion zone and the closest downstream  
75 deposit zone (e.g., Ashmore and Church, 1998; Carson and Griffith, 1989; Eaton and Lapointe, 2001;  
76 Gaeuman et al., 2003; Lane et al., 1995; Neill, 1971, 1987). This assumption has been extensively  
77 explored using various approaches that aim to estimate the transported volumes by applying the inverse  
78 method (Ashmore and Church, 1998; Church, 2006). Furthermore, the influence of bed morphology on  
79 travel distance, real or presumed, is more or less explicit in numerous studies (e.g., Beechie 2001;  
80 Hassan and Church, 1992; Hassan et al., 1991; Hassan and Bradley, 2017; Kasprak et al., 2015; Kondolf  
81 and Matthews, 1986; Lamarre and Roy, 2008; McDowell and Hassan, 2020; McDowell et al., 2021;

82 McEwan, 2001; McQueen et al., 2021; Papangelakis and Hassan, 2016; Pyrcce and Ashmore, 2003a,  
83 2003b, 2005; Schmidt and Gintz, 1995; Sear, 1996; Vázquez-Tarrío et al., 2019).

84 According to Pyrcce and Ashmore (2003a, 2003b), the distribution of transport distances can be  
85 categorised into four types, as distinguished by the intensity and duration of bedload-mobilizing events.  
86 The first two types (types A and B in Pyrcce and Ashmore, 2003a) correspond to non-morphogenic  
87 events. In both, the vast majority of particles are not mobilized or only transported over very short  
88 distances; bedload displacements are hardly, or not at all, controlled by the bedforms, and; shear stresses  
89 are slightly higher than the critical stress value and transport is partial. The last two types (types C and  
90 D) correspond to morphogenic events. In both, transport distances are less dependent on the duration  
91 and magnitude of floods, and instead increasingly influenced by bed morphology; shear stresses exceed  
92 greatly the critical stress value and the bed eventually becomes fully mobile. Thus, in the case of  
93 competent events that are sufficiently long and intense, the modal displacement distance is only partially  
94 determined by flood characteristics (duration or intensity). Most of the material is then deposited on  
95 bars. For riffle-pool systems, transport distances are equivalent to the distance between a pool and the  
96 downstream bar; i.e., the distance separating two successive identical geomorphological units (Pyrcce  
97 and Ashmore, 2003a, 2003b, 2005). Finally, during the longest and/or most intense floods, transport  
98 distances are mainly controlled by the characteristics of hydrological events (Pyrcce and Ashmore, 2003a,  
99 2003b, 2005; Reid et al., 2007). These events are potentially able to either remodel or destroy the original  
100 morphology of the bed, by removing or remodelling the bars—thereby in effect limiting their influence  
101 on transport distances—or remobilizing particles after their initial deposition on bars. Although based  
102 on many field studies and flume experiments, this conceptual model needs to be tested against a larger  
103 range of rivers and conditions to further assess its validity (Pyrcce and Ashmore, 2003a). Alternatively,  
104 Pyrcce and Ashmore (2003a, 2005) also argued that the development and maintenance of these bedforms,  
105 especially bars, requires the occurrence of hydrological episodes able to transport the bedload over a  
106 distance similar to that between two successive bars, equivalent to the length of a single riffle-pool unit.  
107 The existence of such morphology is hypothesized to result from the “net outcome of individual particle  
108 displacements from discrete erosion loci” (Pyrcce and Ashmore, 2003a). However, that would imply that  
109 bedforms are shaped by hydrological events with sufficient power for full mobility to occur, which

110 raises the question of whether such morphogenesis processes actually occur in low-energy gravel-bed  
111 rivers flowing in a temperate environment, notably those having coarse bedload particles. Indeed, in the  
112 case of most gravel-bed rivers, and more so for low-energy rivers, the highest shear stresses attained are  
113 often only slightly greater than the critical shear stress. According to earlier work by Parker et al. (1982),  
114 the ratio between the Shields stress and the critical Shields stress in most gravel-bed rivers almost never  
115 exceeds a value of 2–3. Nevertheless, full mobility may only occur when this ratio is  $> 2$  (Wilcock and  
116 McArdeell, 1993; Church and Hassan, 2002; Recking, 2010). Furthermore, in temperate environments,  
117 the difference in energy between frequent and rare flood events is generally low (Baker, 1977; Kochel,  
118 1988; Lewin, 1989; Magilligan, 1992). These diverse aspects imply that in such systems, at least for  
119 some, full mobility would be rarely attained (Church, 2006; Haschenburger, 2017; Haschenburger and  
120 Wilcock, 2003). Yet, paradoxically, many of these rivers have a clearly discernible riffle-pool structure.

121 Here, we mainly examine the two sides of the conceptual model of Pyrcce and Ashmore (2003a,  
122 2003b), by conducting an in-depth case study of a low-energy gravel-bed river. We focus on the  
123 interactions between transport distance and morphogenesis in a meandering reach of the Cher River in  
124 France across different temporal scales. Because of this river's low energy, we formulated two principal  
125 hypotheses, both related to the assumed low event transport distances. First, only those particles located  
126 at very close distances to bars could become trapped in them. Second, bedforms would be maintained  
127 without the need of transport events whose distance is at least equal to the length scale of the riffle-pool  
128 units.

129 To that end, using PIT tags, annual and decadal bedload transport distances were measured  
130 between 2010 and 2020 along a meander bend. The distance travelled by the bed surface  $D_{50}$  at either  
131 time scale was compared to that estimated according to recent bedload formulas. The ones best able to  
132 predict the tagged particle distance at both yearly and decadal scales were then used to determine the  
133 event transport distance for the entire discharge record period (i.e., 1988–2020) and then infer the  
134 centennial bedload distance. Next, the distances obtained at the event and decadal scales were compared  
135 to the distance separating successive identical geomorphic units. Finally, the tracers' 10 years of data  
136 was used to investigate (1) the variability in bed mobility and velocity according to year, type of  
137 geomorphic unit, and method of tracers' injection, and; (2) the way in which tracers were mixed within

138 the active layer. A key assumption being that the river's low energy confers a long-term persistence of  
139 the effect on bedload velocity estimation arising from where, when, and how tracers are seeded.

140

## 141 **2. Study site**

142 After leaving its source at 713 m a.s.l., the Cher River mainly flows through gorges across steep slopes  
143 or in deep valley with a very narrow floodplain (upstream Cher in Figure 1). The 63-km-long upstream  
144 reach of the river is located at the northwest end of the low-elevation mountainous Massif Central  
145 (France), which mainly consists of crystalline and metamorphic rocks (Larue, 1981, 2011). Then, the  
146 alluvial plain begins (Alluvial Cher in Figure 1), and the river becomes single thread with a meandering  
147 pattern that developed over the last millennia (Vayssière et al., 2020). After first occupying the Tertiary  
148 graben of Montluçon, running 45 km to the confluence with the Aumance River (Larue, 1981, 2011;  
149 Simon-Coinçon et al., 2000), the river then crosses the sedimentary domain of the Parisian Basin, where  
150 it joins the Loire River at a 38 m a.s.l.

151 At the reference gauging station for our study site (Figure 1), the mean annual discharge is 14.8  
152  $\text{m}^3 \text{s}^{-1}$ . The rainfall regime is typical of lowland rivers on the western facades of mid-latitude regions.  
153 The minimum and maximum monthly discharges occur respectively in August and February. The  
154 hydrological regime, particularly the low-flow regime, is partly affected by the Rochebut Dam, it located  
155 45 km upstream of the study reach, whose construction was completed in 1909 (Figure 1). Initially built  
156 exclusively for electricity production, the dam has since been relied on to provide low-water support for  
157 several decades now.

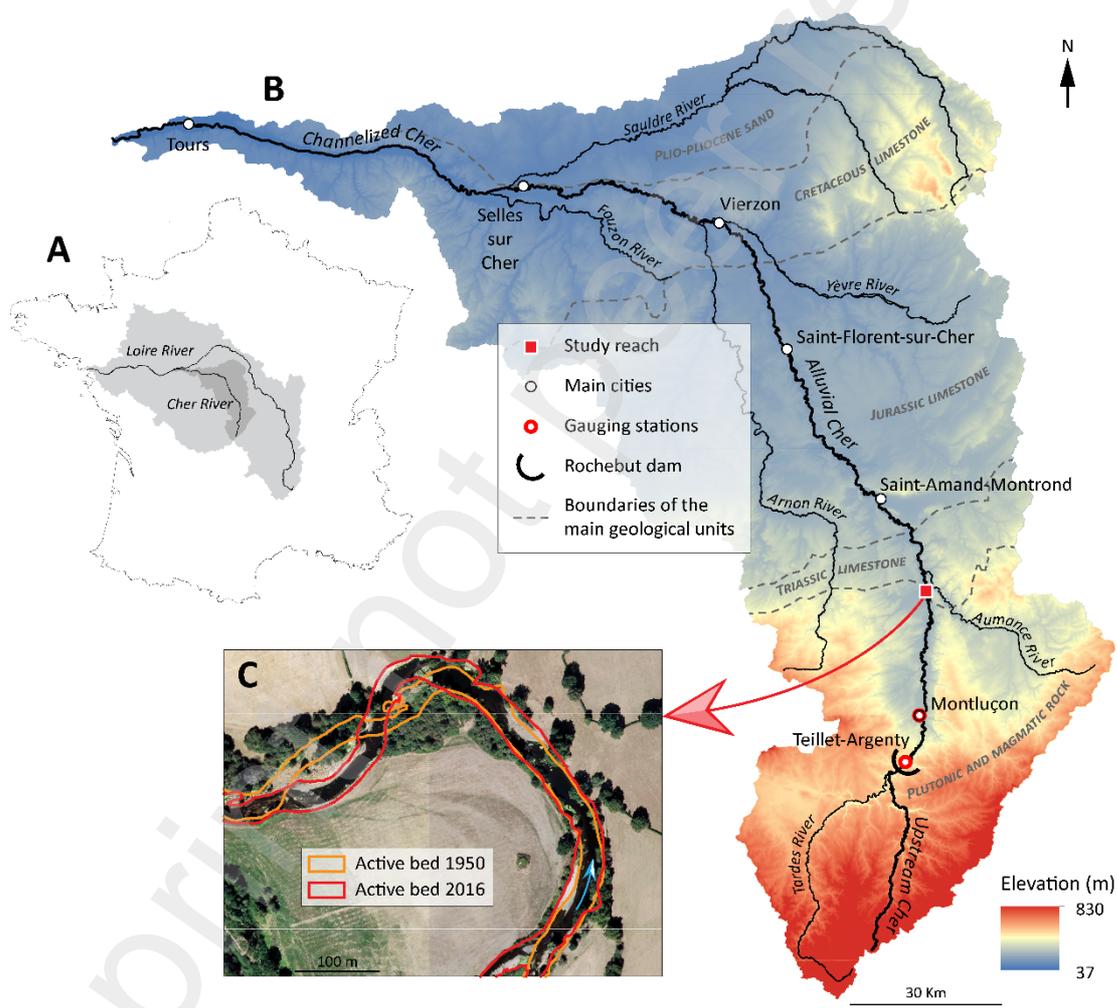
158 The study reach spans more than 700 m along a meander bend located in the Tertiary graben  
159 of Montluçon (Figure 1). Its bedrock is composed of Eocene and Oligocene sand and clay on the left  
160 side of the valley, and of Triassic sand more or less clayey on its right side (Turland et al., 1989a). The  
161 alluvial infilling is schematically organized into two or three main stratigraphic levels. The base of the  
162 infilling consists of sand, gravel, and pebble while its upper part consists of overflow deposits of clay,  
163 silt, and sand (Dépret, 2014; Turland et al., 1989b); between these two levels, a predominantly sandy  
164 layer is often interspersed. Because of this composite structure and the coarse nature of its material, the  
165 banks are highly erodible (Dépret et al., 2015, 2017). But due to the presence of ancient fluvial

166 engineering works, especially those protecting the bank, the historical mobility of the reach is low  
167 (Dépret et al., 2015, 2017).

168 The active channel width is 32 m, the low-flow bed slope is 0.001133 m m<sup>-1</sup>, and the bankfull  
169 discharge is 85 m<sup>3</sup> s<sup>-1</sup> at the reference gauging station, this one located at Montluçon (Figure 1). With a  
170 surface D<sub>50</sub> and D<sub>84</sub> of 28 and 48 mm, respectively, and a bankfull specific stream power of 30 W m<sup>-2</sup>  
171 (computed from the active channel width), it is a low-energy river with a coarse gravel bed (Dépret,  
172 2014; Dépret et al., 2015). In the study bend, the armour ratio for the D<sub>50</sub> and the D<sub>84</sub>, as determined in  
173 two riffles, is equal to 2.7–3.2 and 1.3–1.5, respectively (Dépret, 2014). These relatively low values are  
174 consistent with the quite high frequency of mobilization of D<sub>50</sub> (34 days y<sup>-1</sup> for a critical discharge of 40  
175 m<sup>3</sup> s<sup>-1</sup>) and the fact that the whole grain-size spectrum can be mobilized for discharge below the bankfull  
176 (Dépret et al., 2017). These features strongly suggest a relatively weak sedimentary deficit, and thus, at  
177 worst, a slight reduction in bed mobility because of the fluvial engineering works' presence or due to  
178 the Rochebut Dam. An absence of the latter's influence is explained by the very lightly modified  
179 hydrological regime for a discharge higher than the critical discharge, and by the fact that the total  
180 interruption of the bedload continuity it has induced has not yet affected the study site. Comparing the  
181 natural reconstructed daily discharge at the dam's outlet (powered discharge + variation of water level  
182 in the reservoir + discharge above the crest of the dam; data provided by Electricité de France) with the  
183 actual daily discharge outflowing from it (powered discharge + discharge above the crest of the dam;  
184 data from <https://hydro.eaufrance.fr/>) shows that the annual number of days exceeding the critical  
185 discharge is 1.2-times higher for the former than the latter. Concerning the peak of competent events,  
186 the actual discharge values are just slightly lower than the natural reconstructed ones (ActualQ = 1.04 ×  
187 NaturalQ – 6.7, R<sup>2</sup> = 0.95). Lastly, the distance between the Rochebut Dam and the study site is more  
188 than 10-fold the distance travelled by bedload since the dam's completion. Hence, the bedload deficit  
189 due to the dam could not have yet reached the study site.

190 The bedforms are organized into well-developed riffles and pools, some of them forced due to  
191 the presence of the fluvial engineering works in the bed (Buffington et al., 2002; MacVicar et Roy,  
192 2011; Thompson et Wohl, 2009). Therefore, the pools P1 and P2 can be separated in two sub-pools  
193 (named A and B) according to the presence of a structure similar to a groyne (Figure 2). P3 is also

194 separated into two sub-pools (A and B) according to the presence of remnants of bank protections in the  
 195 bed. P1B, P2B, and P3B are thus at least partly forced. Furthermore, the pool P3A as well as the riffle  
 196 R3 are also probably forced given the presence of two crosswise, parallel alignments of piles on the  
 197 right half of the bed, these exhumed due to bank erosion over recent decades (Figure 2). Furthermore,  
 198 some bars are evident. The two main ones are situated at the upstream and downstream boundaries of  
 199 the bend equipped with tracers (Figure 2). The downstream one (B4) is located along the study reach's  
 200 main section, where lateral mobility has occurred in the last decades. For this reason, it has grown  
 201 laterally during the study period, whereas the other bars have remained more stable.



202  
 203 Figure 1 – Study site localization. A: The Cher River watershed within French territory. B: The study  
 204 reach in the Cher River watershed. C: Zoom on the study reach.

205  
 206

### 207 3. Material and methods

#### 208 3.1 PIT-tags and bedload velocity from 2010 to 2020

209 Bedload velocity was estimated at an annual and decadal scale on a meander bend by tracking particles  
210 equipped with passive transponders (Texas Instruments RFID chips, length: 12–23 mm, emission  
211 frequency: 134.2 kHz). A total of 1503 tagged particles were injected in 2010, 2011, and 2012 into the  
212 different geomorphological units of the bend (i.e., riffles, pools, bars) as well as into the two active  
213 banks and at their toe (Figure 2). Previously, the geomorphic units were identified visually and  
214 delineated with an RTK-DGPS: we distinguished riffles, pools, bars and also the main glides or runs.  
215 Portions of some pools were also apparently forced (see section 2). Two injection strategies were used  
216 in tandem, whereby tracers were introduced individually or in clusters. Individual tracers were injected  
217 in 2010 and 2012 at 50-cm intervals along cross-sections located at the head of riffles. The total number  
218 of particles per cross-section ranged from 32 to 53. Clusters were injected in 2010 and 2011, with 40  
219 particles per cluster. In 2010, they were deposited in the centre of each of riffle and likewise in two of  
220 the pools (P1A, P2B), and also at the head of the main migrating bar (B4) and in the banks as well as at  
221 their toe (Figure 2). An identical strategy was implemented for the 2011 clusters, this time with all the  
222 pools and the upstream run equipped with them (Figure 2). Clusters at the bank toe were positioned  
223 midway between the upstream and downstream limits of the active banks. Clusters in banks were  
224 positioned at three longitudinal locations: at the vertical of the clusters located at bank toe, and midway  
225 between that point and the upstream or downstream limit of the active banks. Two clusters per vertical  
226 were placed in the upstream bank (at mid-height and between that and the top of the bank), one in the  
227 downstream bank (at mid-height). Except for the deepest pools (i.e., P1A, P1B, P2B, cf. Figure 2), all  
228 the tagged particles were inserted into the pre-existing sedimentary structure, in order to avoid artificial  
229 overexposure to the flows. For riffles, the particle size of tagged particles corresponds to the channel's  
230 surface particle size (from 22.6 mm), as determined in 2010 by sampling 400 particles according to the  
231 Wolman's methodology (1954). For the other geomorphic units, the tracers' particle size distribution  
232 was the same as that for the riffle located immediately upstream. Each half-phi size-class was tagged  
233 between 22.6 and 90.5 mm. For banks, only the 22.3–32 mm and the 32–45 mm classes were equipped.  
234 Three detection surveys were carried out in summer at low flow, one each in 2011, 2012, and 2020

235 (detection system built by CIPAM). The detection front was located 180 m from the downstream-  
236 injection cluster in 2011 and 2012 (for a maximum and a 99% percentile of particle distances of 232 m  
237 and 117 m, respectively, for the 2010–2012 period). In 2020, the detection front was located 1200 m  
238 from the downstream-injection cluster (maximum and 99% percentile of particle distances of 1200 m  
239 and 720 m, respectively from 2010/2011/2012 to 2020). The position of each particle was surveyed  
240 manually with an RTK-DGPS in the wadeable portions of the bed. For the rest of the bed, particles'  
241 detection required the use of a boat. In 2011 and 2012, the boat was attached to ropes stretched across  
242 the bed; in 2020, their detection was performed with an electric motor boat, the RFID reader and the  
243 RTK-DGPS being connected to a laptop, with the position and identification of every tracer  
244 automatically recorded (ArpenGIS software).

245 For particles individually injected along the cross-sections, the critical distance of mobilization  
246 was set to 40 cm, which corresponds roughly to the maximum detection range of the antenna (Arnaud  
247 et al., 2015; Chapuis et al., 2014). For clusters, the determination of this distance took into account the  
248 uncertainty related to the initial position of each particle, as well as any uncertainty concerning the  
249 location of the particles at the time of their detection. The exact initial position of each particle could  
250 not be precisely known because we only had the coordinates for the centre of each cluster. Therefore,  
251 the value of the first type of uncertainty is equal to the radius of clusters (40 cm in 2010, and 30 cm in  
252 2011). The second type of uncertainty is linked to the maximum detection range (20 cm) of the small  
253 antenna used to detect tracers located near the clusters. For most clusters, the total uncertainty, and hence  
254 the critical distance of mobilization, was 60 cm (40 cm + 20 cm) for the 2010 particles and 50 cm (30  
255 cm + 20 cm) for the 2011 particles. For some clusters located in pools, the critical distance was longer  
256 because of greater uncertainty associated with the initial position and/or location of the particles (2 m  
257 for M1A, P1B, and P2B; 0.8 m for P3A, P3B, and P4).

258

### 259 **3.2 Characterization of bedload mobility, velocity, and trajectory at a decadal scale**

260 For all particles, and likewise for each half-phi grain-size class, we first calculated the recovery rate, the  
261 mobilization rate, as well as the mean and median distances travelled by the detected particles  
262 (mobilized and non-mobilized). We also investigated how these parameters varied by date, by unit, and

263 by method of injection (cross-sections or clusters). To enable such comparisons, we distinguished those  
264 particles injected in clusters into the same units in 2010 and 2011 (i.e., five riffles and two pools),  
265 particles injected in clusters into riffles only in 2010 and 2011 (fives riffles), particles injected along  
266 cross-sections in 2010 and 2012 (four riffles), particles injected in clusters into pools in 2010 and 2011  
267 (two pools in 2010, seven in 2011).

268         Next, we examined the distances and trajectories of particles, to determine how they interacted  
269 with the river's size and its geomorphic units, especially bars. To do that, we first calculated the  
270 percentage of particles (mobilized and non-mobilized) that were deposited in their unit of injection or  
271 in the downstream one. Then we compared the 10-year distance travelled by particles (= 10 times the  
272 annual velocity of 2010 or 2011 or 2012 particles between their year of injection and 2020) to the median  
273 distance between successive riffles and between successive pools (110 m); the percentage of travelled  
274 distances lower than the median distance between units was determined. We also characterized the  
275 influence of the only laterally developing and migrating bar (B4) upon the trapping efficiency of  
276 particles at a decadal scale. For each geomorphic unit of tag injection upstream of the bar (all dates,  
277 clusters, and cross-sections taken together), we looked at the percentage of all particles and those of  
278 22.3–32 mm in size that got trapped in the bar and examined how it varied with distance to the bar.  
279 Finally, we focused on particles injected in banks and at the bank toe, to better understand how particles  
280 eroded from the banks are redistributed in the active channel.

281

### 282         **3.3 Distribution of particle velocities at a decadal scale**

283         The shape of the velocity distribution and of its tail was examined, to gain insight into the dispersion of  
284 tracers occurs and because it has major implications for modelling advection-diffusion processes  
285 (Haschenburger, 2013; Hassan et al., 2013; Hassan and Bradley, 2017). First, we determined how well  
286 (or not) various probability distributions widely tested in the literature fitted with the annual velocity  
287 distribution (for all generations of tagged particles taken together and for each generation considered  
288 individually, for all particle sizes and only those 22.3–32 mm in size). Following the probability  
289 distributions tested by Haschenburger (2013) and Papangelakis and Hassan (2016), and according to the  
290 shapes of the annual velocity distributions, we tested four types of probability distributions using the

291 'fitdistrplus' package in R (Delignette-Muller and Dutang, 2015): the exponential, gamma, Pareto, and  
 292 Weibull. Akaike's Information Criterion (AIC) was used as goodness-of-fit criterion between the  
 293 probability distributions (Delignette-Muller and Dutang, 2015). Second, we focused on the behaviour  
 294 of the distributions' tail. To do this, we implemented two approaches developed by Hassan et al. (2013).  
 295 In one, a power law is fitted to the tail of the exceedance probability distribution of tracer velocities,  
 296 using ordinary least-squares regression, and the fitted power value examined. Heavy and thin tails  
 297 respectively correspond to a log-log slope of the exceedance tail of  $\alpha < 2$  and  $\alpha > 2$ . The other  
 298 approach relies on Hill's estimators (Hill, 1975), a ranking method based on the conditional maximum  
 299 likelihood estimator for the power and slope in the Pareto distribution  $P(X > x) = Cx^{-\alpha}$  fitted to the  
 300 tail of sample data:

$$301 \quad \alpha_H = r \left[ \sum_{i=1}^r (\ln X_i - \ln X_{(r+1)}) \right]^{-1}; C_H = \frac{r}{n} (X_{(r+1)})^{\alpha_H}$$

302 where  $\alpha_H$  and  $C_H$  are estimators for power and slope, respectively;  $X_i$  are the order statistics such that  $X_1$   
 303  $\geq X_2 \geq \dots X_n$ ; the  $r$  is the rank of the smallest data point in the tail of the distribution. When  $\alpha_H < 2$ ,  
 304 the distribution is considered to be heavy-tailed.

305

### 306 **3.4 Estimation of bedload distance at the event-based and century scales**

307 To estimate the bedload velocity at the event-based scale, we tested the most recent formulas published  
 308 in the literature (eq. 4 in Gilet et al., 2020; eq. 13, 14 for all rivers, eq. 14 for riffle-pool rivers, and eq.  
 309 15 for riffle-pool rivers in Vázquez-Tarrío and Batalla, 2019; eq. in figure 2 for riffle-pool rivers with  
 310 width/depth bankfull ratio  $> 10$  in Vázquez-Tarrío et al., 2019; eq. for riffle-pool rivers in figure 4 in  
 311 Vázquez-Tarrío et al., 2019; eq. for all rivers except for the unconstrained step-pool rivers in Figure 9  
 312 in Vázquez-Tarrío et al., 2019). Derived from field data, these formulas relate the event bedload velocity  
 313 or distance to different controlling parameters, such as flood magnitude and duration, grain-size of the  
 314 bed, and the width and slope of the river, among others. Here we selected the ones providing the closest  
 315 estimate of empirical distances travelled by the PIT-tags in the periods 2010–2011, 2011–2012, 2010–  
 316 2020, 2011–2020, and 2012–2020. Here we postulated that if the formulas are robust for reconstructing  
 317 the cumulative event bedload distance at yearly and decadal scales, they should be reliable for estimating

318 the event bedload distances. On this basis, the chosen formulas were applied to each competent event  
319 that occurred for the entire daily discharge record period (i.e., 1988–2020 at the Montluçon reference  
320 gauging station). The critical discharge for incipient motion was first estimated from presence–absence  
321 PIT-tags surveyed at different discharge values between 2010 and 2012 along the cross-sections located  
322 at riffle heads (Dépret et al., 2015, 2017) (R1, R3, R4, R5, cf. Figure 2). It was also estimated from six  
323 20-mm sensitive ‘Benson-type’ seismic impact plate sensors (Downs et al., 2016), these equally spaced  
324 along a cross-section located at the riffle head on the bend downstream of the PIT-tag bend, which  
325 recorded data during the 2018–2019 high-flow period. Both approaches provided an estimation of the  
326 critical discharge equal to  $40 \text{ m}^3 \text{ s}^{-1}$  at the Montluçon reference gauging station. In addition to the critical  
327 discharge, to apply the formulas three other parameters must be known: the surface grain-size, the bed  
328 slope, and the active channel width. Surface grain-size was determined from low-flow photographs in  
329 2018 of coarse grain-size patches of each bar. The photographs were taken vertically with the scene  
330 hidden from direct solar radiation, at a high enough resolution to distinguish particles as small as coarse  
331 sand. Using GIS (ArcGIS 10.6), we measured the apparent b-axis of 100 particles located at intersections  
332 of a regular grid on the photo, whose spacing was higher than the maximum longest axis (a-axis). The  
333  $D_{50}$  and  $D_{84}$  used in formulas corresponded to the interpolated  $D_{50}$  and  $D_{84}$  of bars (28–48 mm), being  
334 very close to the values obtained from the Wolman samples on riffles in 2010 (25–44 mm). The slope  
335 was surveyed at low flow with a RTK-DGPS in 2020. The active channel width was reconstructed from  
336 a 2016 aerial orthophotograph (provided by the IGN: Institut Géographique National) analysed in GIS;  
337 after the active channel’s digitization, its surface area was divided by the length of the study reach to  
338 obtain the average width.

339

### 340 **3.5 Interactions between bedforms and bedload distance at the event scale**

341 For a channel-forming discharge, namely for conditions of full mobility, and in the presence of well-  
342 developed riffle-pool morphology, the modal event bedload velocity should be controlled by the  
343 distance separating a pool to the bar located immediately downstream, the latter trapping most of the  
344 particles (Pyrce and Ashmore, 2003a, 2003b). Conversely, this implies that for such a discharge,  
345 particles should be able to displace to a distance at least equal to that separating two successive identical

346 geomorphic units. To test where that applies to the Cher River, we compared the event distances to the  
347 median distance between successive riffles and between successive pools (sub-pools considered here as  
348 individual units). The conditions for full mobility are theoretically reached when the grain shear stress  
349 exceeds twice its critical value (Wilcock and McArdeell, 1993; Church and Hassan, 2002; Recking,  
350 2010). To determine if events with full mobility had occurred from 1988 to 2020, the shear stress value  
351 for which full mobility begins was derived, using two slightly different methods. In the first one, we  
352 followed Recking et al.'s (2016) formula for riffle-pool rivers, which estimates the Shields stress  
353 corresponding to the transition from partial to full mobility:

$$\tau_m^* = (5S + 0.06) \left( \frac{D_{84}}{D_{50}} \right)^{4.4}$$

354  
355 where  $S$  is the bed slope (in  $\text{m m}^{-1}$ );  $D_{50}$  and  $D_{84}$  respectively are the median and 84<sup>th</sup> percentile of the  
356 surface grain-size distribution (in m).  
357

358  
359 In the second method, we calculated the Shields stress value for the critical discharge, this  
360 corresponding to incipient partial transport, multiply it by two to determine the Shields stress for full  
361 mobility. The critical Shields stress was computed for the  $D_{84}$ , since it allows approaching the grain  
362 stress without any bias (Recking et al., 2016), as follows:

$$\tau_c^* = \frac{\tau}{(\rho_s - \rho)gD_{84}}$$

363  
364 where  $\rho_s$  is the density of sediment,  $\rho$  is the water density, and  $\tau$  is the critical bed shear hear stress (in  
365  $\text{N m}^{-2}$ ), the last obtained this way:  
366

$$\tau = \rho g S d$$

367  
368  
369 where  $g$  is gravity acceleration ( $9.81 \text{ m s}^{-1}$ );  $d$  is the average flow depth (in m), computed as follows  
370 from the approximation of Rickenmann and Recking (2011) proposed by Recking et al. (2016):  
371

372

373 
$$d = 0.015D_{84} \frac{q^{*2p}}{p^{2.5}}$$

374 where  $p = 0.24$  if  $q^* < 100$  or  $0.31$  otherwise (which is the case of our study reach), and  $q^* =$   
375  $q/w\sqrt{gSD_{84}^3}$ , for which  $q$  is the water discharge (in  $\text{m}^3 \text{s}^{-1}$ ).

376

377 For overbank flows (i.e., those  $> 85 \text{ m}^3 \text{ s}^{-1}$ ), the discharge  $q$  used is the one for the prism over  
378 the channel. The bed mobility is controlled by this discharge value rather than by the total discharge.  
379 Following Dépret et al. (2015), we used the results of a hydraulic modelling done in 1998 (Direction  
380 Départementale de l'Allier, 1998) for seven flood discharge values along a cross-section located at riffle  
381 R1. From it, a power law was obtained to predict the discharge over the channel as a function of total  
382 overbank discharge:

383

384 
$$q = 9.872Q_{tot}^{0.487}$$

385

386 where  $Q_{tot}$  denotes the total overbank discharge (in  $\text{m}^3 \text{ s}^{-1}$ ).

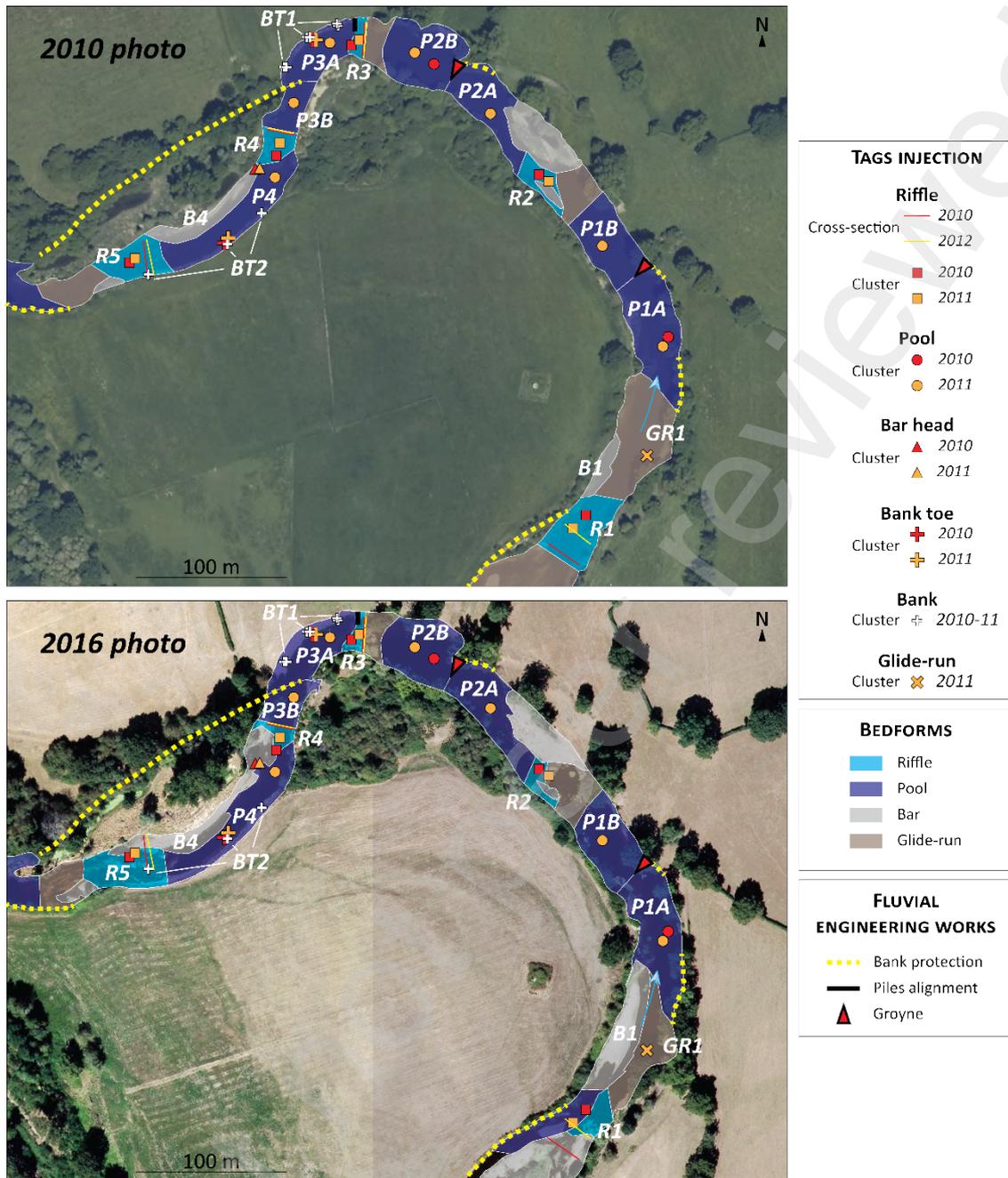
387

388 Then, according to both methods, we determined the discharge corresponding to the Shields  
389 stress for full mobility. Each value was compared to the peak discharge of each competent event, to  
390 identify those events in which the theoretically full mobility had occurred. Finally, for each event, we  
391 compared the mean bedload distance to the median distance between riffles and between pools (110 m).

392

393

394



395

396 Figure 2 – Localization of the PIT-tags’ injection and of the fluvial engineering works in the study reach;  
 397 delineation of the main geomorphic units in 2010 and 2020.

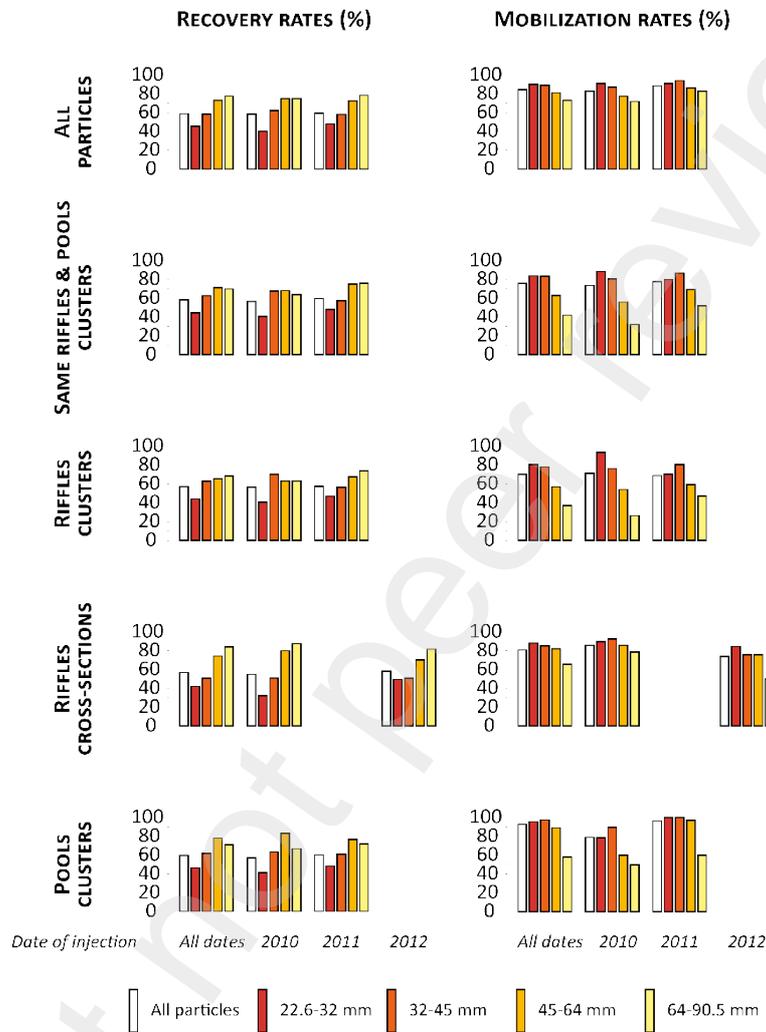
398

#### 399 4. Results

##### 400 4.1 2010-2020 recovery rate and mobilization rate

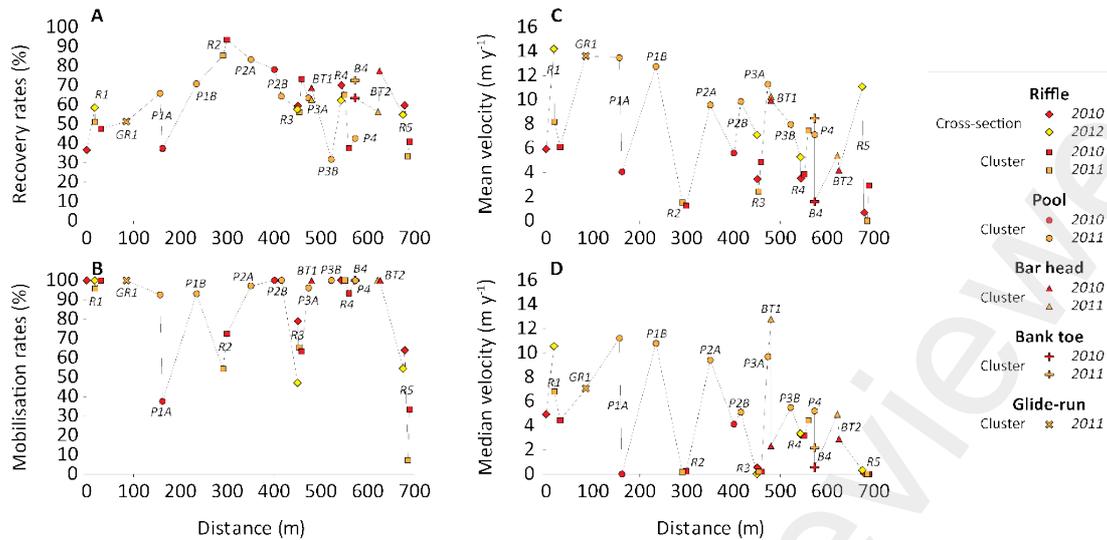
401 The recovery rate for all particles injected into the bed across all dates is 59% irrespective of injection  
 402 year (Figure 3). Moreover, it increased with particle size: being 45% (40%– 49% according to the  
 403 injection year), 59% (51%–62%), 73% (70%–75%, 78% (75%–82%) respectively for the particle size-

404 classes of 22.3–32 mm, 32–45 mm, 45–64 mm, and 64–90.5 mm (Figure 3). For particles injected into  
 405 banks, the overall recovery rate was 53% (52% for injected particles in 2010, 55% for those in 2011).  
 406 Considering individual injection points (cluster or cross-section), the recovery rates varied from 32% to  
 407 100% (Figure 4A).



408

409 Figure 3 – Recovery rates and mobilization rates of tracers from 2010/2011/2012 to 2020.



410

411 Figure 4 – Longitudinal pattern of recovery rates (A), mobilisation rates (B), mean velocity (C), and  
 412 median velocity (D) for all particle size-classes taken together.

413

414 The mobilization rate for all particles injected into the bed for all dates is 84% (83% for 2010 particles,  
 415 89% for 2011 particles, and 73% for 2012 particles). It decreased slightly when the particle size  
 416 increased from the 22.6–32 mm to the 45–64 mm size-class, but dropping sharply for the coarser class  
 417 (64–90.5 mm). Rates were 90% (85%–91% according to the injected year), 89% (76%–94%), 81%  
 418 (76%–86%), 73% (50%–83%) for particle size-classes of 22.3–32 mm, 32–45 mm, 45–64 mm, and 64–  
 419 90.5 mm, respectively. For particles injected into the banks, the mobilization rate is 100% because of  
 420 the bank retreat that occurred between 2010 and 2020. If we consider individually the injection points  
 421 (cluster or cross-section), the mobilization rates varied from 7% to 100%, the second lowest rate being  
 422 relatively higher at 33% (Figure 4B). Lastly, we observed a net difference in mobilization rates  
 423 according to the year, the type of geomorphic unit, or even the injection method (cluster or cross-section)  
 424 of tagged particles. The general pattern was of higher rates for 2011 particles, for particles injected in  
 425 pools, and for particles injected along cross-sections (Figure 3, Figure 4B).

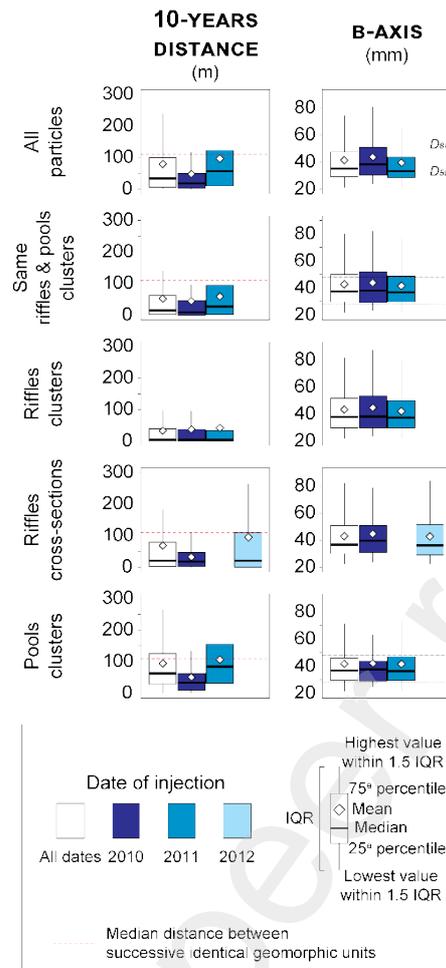
426

427 **4.2 2010-2020 bedload velocity**

428 The mean and median velocity for all particles injected in the bed for all dates are 6.8 m y<sup>-1</sup> and 2.9 m  
 429 y<sup>-1</sup>, respectively (Figure 5). Moreover, the velocity decreases with increasing grain-size: its mean

430 (median) is respectively 13 (7.1) m y<sup>-1</sup>, 6.7 (4.6) m y<sup>-1</sup>, 3.2 (1.6) m y<sup>-1</sup>, and 1.1 (0.5) m y<sup>-1</sup> for particle  
431 size-classes of 22.3–32 mm, 32–45 mm, 45–64 mm and 64–90.5 mm, respectively (Figure 6). In terms  
432 of individual injection points in the bed (cluster or cross-section), the mean and median velocities varied  
433 from 0.01 m y<sup>-1</sup> to 14.2 m y<sup>-1</sup> and from 0 m y<sup>-1</sup> to 12.8 m y<sup>-1</sup>, respectively (Figure 4C and D). The  
434 longitudinal pattern shows substantial variability but with slightly higher values along the upstream  
435 stretch of 230–300 m (Figure 6).

436 Furthermore, not unlike the mobilization rates, we observed important variability in the bedload  
437 velocity according to the year of injection, the type of geomorphic unit, and finally the method (cluster  
438 or cross-section) used to inject the tagged particles (Figure 4C, Figure 4D, Figure 5, Figure 6). As these  
439 observations are valid for all grain-size classes (taken individually or together), we go on to detail these  
440 points solely for the 22.6–32 mm size-class. We did so for clarity of purpose and because the velocity  
441 of particles belonging to this class and that of D<sub>50</sub> can be deemed reasonably similar: whichever way the  
442 tagged particles are considered (by year or unit or method of injection), the mean and median grain-size  
443 for the 22.6–32 mm size-class of the detected particles ranged between 27 and 30 mm, which is very  
444 close to the bed surface D<sub>50</sub> on the studied bend (28 mm).



445

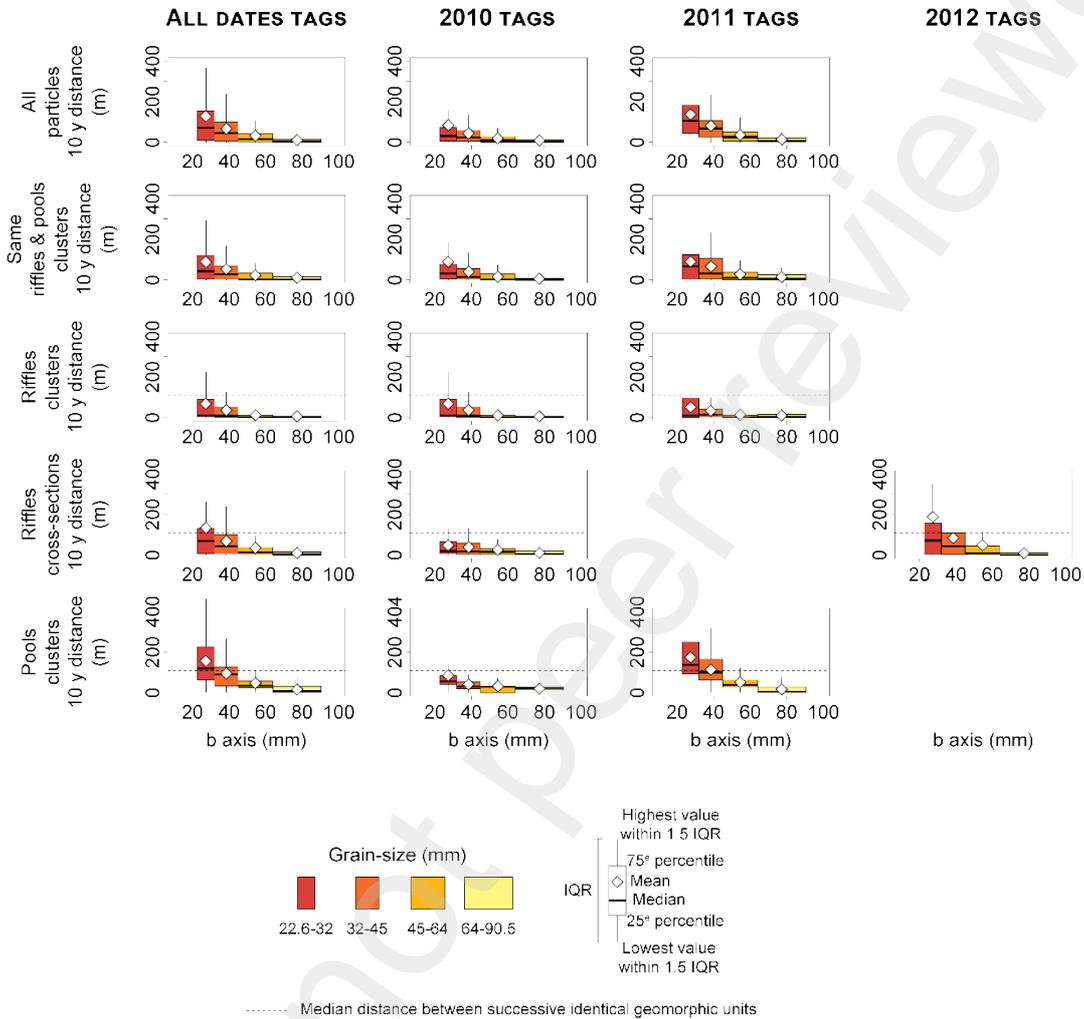
446 Figure 5 – Box-plots of 10-year distances and particle size for all particles grouped by date of injection,  
 447 geomorphic unit and injection method.

448

449 First, the particles injected in 2010 were the slowest: their mean (median) velocity was 8.9 (3.1) m y<sup>-1</sup>  
 450 yet 9.5 (6.9) m y<sup>-1</sup> for the 2011 ones, when focusing on particles injected in clusters on the same riffles  
 451 and pools in both years. For the particles injected individually along cross-sections in riffles in 2010 and  
 452 2012, their velocity was 4.9 (2.1) and 18.8 (7.2) m y<sup>-1</sup>, respectively (Figure 6). Second, the velocity of  
 453 particles injected in pools was greater than that injected in riffles: for the 2010 particles, their velocity  
 454 was 9 (1) m y<sup>-1</sup> for the former versus 8.6 (5.7) m y<sup>-1</sup> for the latter (Figure 6). The difference is more  
 455 pronounced for the 2011 particles: 5.9 (1) m y<sup>-1</sup> for the riffle particles versus 16.9 (16.3) m y<sup>-1</sup> for the  
 456 pool ones (when considering the same pools than in 2010, P1A and P2B; when considering all pools, as  
 457 seen in Figure 6, the velocity is roughly the same: 17.5 (14.2) m y<sup>-1</sup>). Lastly, particles injected along  
 458 cross-sections moved faster than those injected in clusters (comparison only possible for riffles in 2010):

459 the mean (median) is 9 (1) m yr<sup>-1</sup> for the cluster particles and of 4.9 (2.1) m yr<sup>-1</sup> for the cross-section  
 460 particles (Figure 6).

461



462

463 Figure 6 – Box-plots of 10-year distances for each half-phi class size.

464

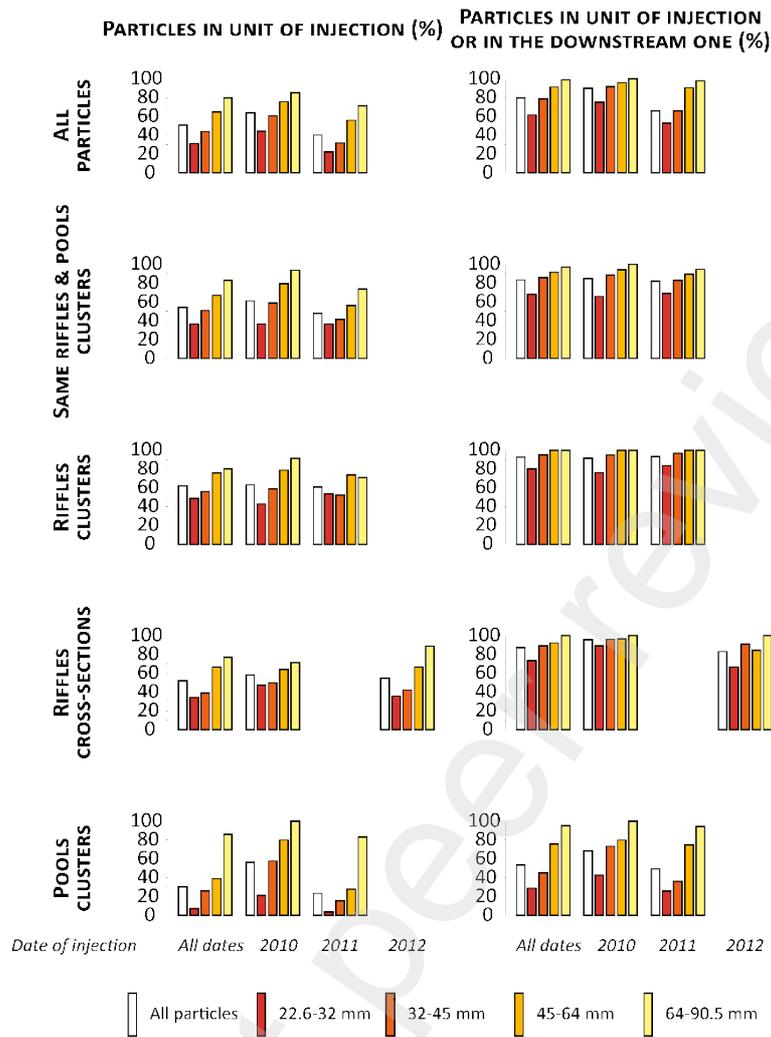
465 For the clusters in banks (BT1 and BT2, cf. Figure 2), the velocity was higher for the 2011 particles and  
 466 those coming from the downstream bank. Specifically, for the only two size-classes equipped with tags,  
 467 the mean (median) velocity was 18.8 (13.8) m yr<sup>-1</sup> for the 22.3–32 mm size-class but lower at 7.8 (3.6)  
 468 m yr<sup>-1</sup> for the 32–45 mm size-class. The velocity for the 22.3–32 mm size-class was similar for the 2010  
 469 and 2011 particles: 16.9 (14.2) versus 19.1 (13.7) m yr<sup>-1</sup>, whereas for the 32–45 mm size-class, it is  
 470 clearly higher in 2011: 9.7 (4.11) versus 5.2 (2.5) m yr<sup>-1</sup>. Moreover, the velocity of particles was clearly  
 471 lower for those injected into the upstream bank (BT1) than downstream bank (BT2): 13.2 (11.7) m yr<sup>-1</sup>

472 versus 30.5 (16.2) m yr<sup>-1</sup> for all particles and all dates. In comparison to particles injected into banks,  
473 the velocity of particles injected at the bank toe was lower for the 22.3–32 mm size-class (14.9 [7.2] m  
474 yr<sup>-1</sup>), but higher for the 32–45 mm size-class (8.6 [6.3] m yr<sup>-1</sup>). Regarding the 2011 particles injected  
475 into banks, they moved faster; however, the velocity of particles injected at the toe were higher for the  
476 upstream bank. In detail, the velocity for the 22.32 mm size-class is 15.8 (4.4) m yr<sup>-1</sup> in 2010 and 13.9  
477 (15) m yr<sup>-1</sup> in 2011. For the 32–45 mm size-class, it was 7.9 (5) m yr<sup>-1</sup> in 2010 and 9.4 (6.9) m yr<sup>-1</sup> in  
478 2011. The velocity of 22.3–32 mm particles injected at the toe of the upstream bank was 23.8 (16.7) m  
479 yr<sup>-1</sup>. For the downstream bank, it was 8.2 (5.8) m yr<sup>-1</sup>. For the 32–45 mm size-class, it was 12.7 (15.6)  
480 m yr<sup>-1</sup> for upstream and 5.1 (4.9) m yr<sup>-1</sup> for downstream.

481

#### 482 **4.3 2010-2020 bedload trajectory**

483 For the study period, half of particles injected into the bed (particles injected at bank toe and in banks  
484 excluded) remained in their geomorphic unit of injection (Figure 7, Figure 8). On a per year basis, the  
485 retained proportions were 64%, 40%, and 55% for the 2010, 2011, and 2012 particles, respectively  
486 (Figure 7). The proportion of particles trapped in their geomorphic unit of injection increased with  
487 particle size, being 31%, 44%, 65%, and 80% for the 22.3–32 mm, 32–45 mm, 45–64 mm, and 64–90.5  
488 mm size-classes, respectively. The individual trajectory of particles can be seen for each size-class in  
489 Figure 8. Furthermore, in 2020, the proportion of particles persisting in riffles surpassed that in pools  
490 (34%–50% for riffles versus 7% for pools), despite much shorter distances from the injection point to  
491 the exit units in riffles (mean, median of 21, 15 m for riffles versus 62, 69 m for pools) (Figure 7). For  
492 the 22.6–32 mm size-class (which encompasses D<sub>50</sub>), most particles initially injected into pools were  
493 deposited outside of them (Figure 7). The difference in proportion between units decreased with particle  
494 size. Lastly, 80% of particles injected into the bed (particles injected at bank toe and in banks excluded)  
495 remained in their geomorphic unit of injection or in that located immediately downstream (Figure 7).  
496 By year, the retained proportions were 90%, 72% and 83% for 2010, 2011 and 2012 particles  
497 respectively (Figure 7). When examined by size-class, the proportions were 62%, 79%, 91%, and 99%  
498 for the 22.3–32 mm, 32–45 mm, 45–64 mm, and 64–90.5 mm classes, respectively.

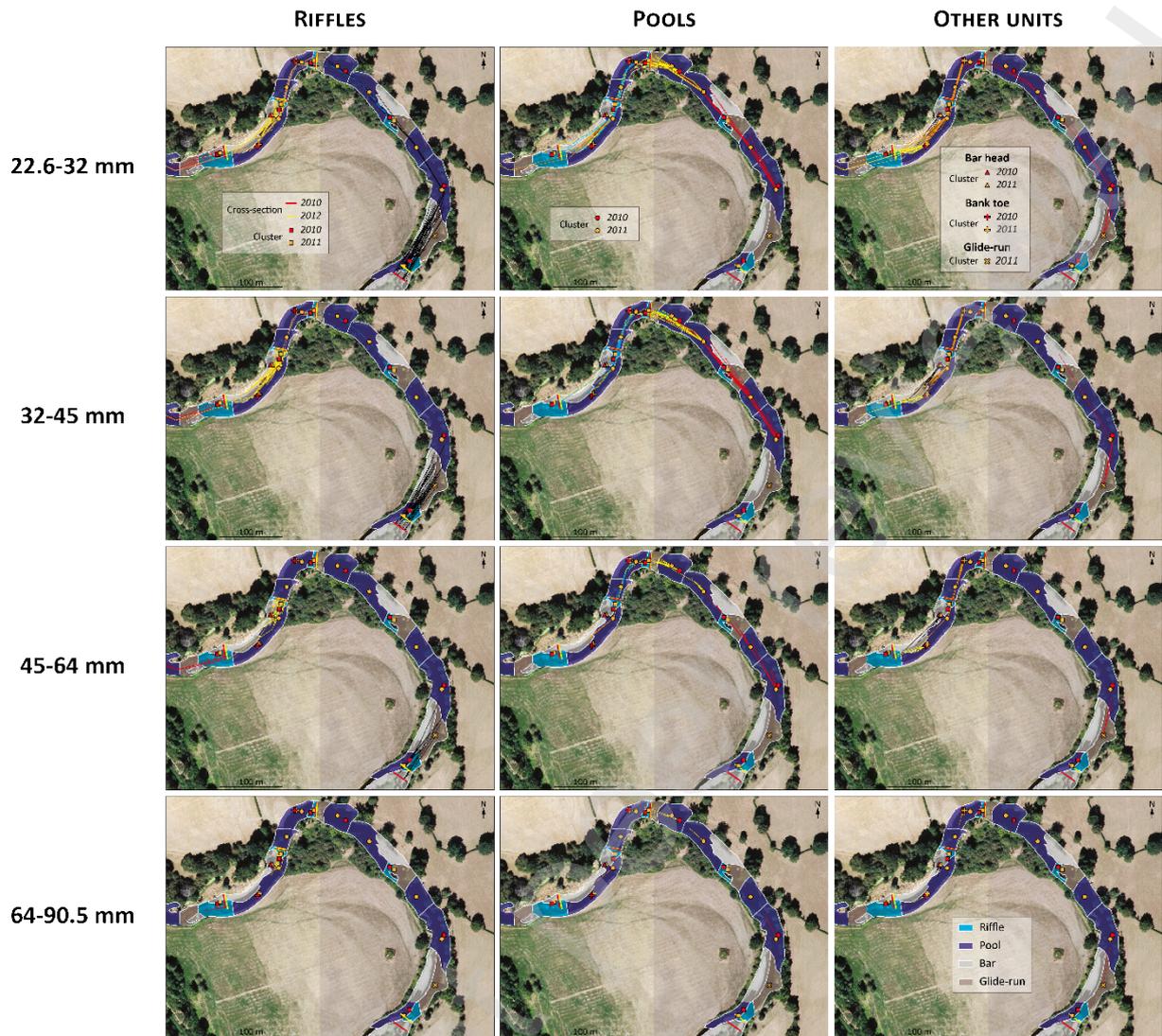


499

500 Figure 7 – Percentage of particles that remained in their unit of injection or deposited in the downstream

501 one in 2020.

502



503

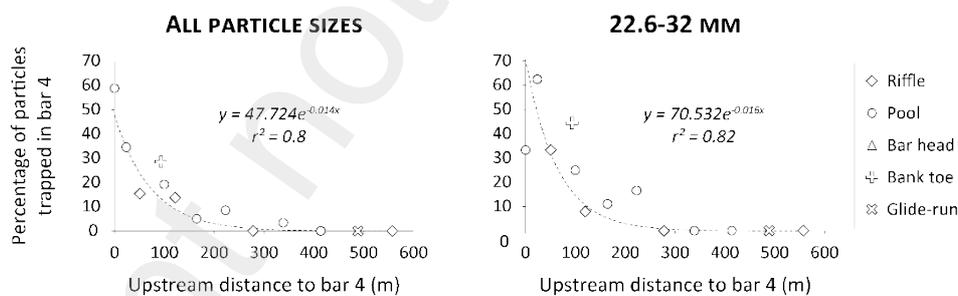
504 Figure 8 – Trajectory of individual tagged particles from 2010/2011/2012 to 2020.

505

506 The question of bedload trajectories was also addressed indirectly, by comparing the 10-year bedload  
 507 velocity with the median distance between successive riffles and between successive pools (110 m). For  
 508 all dates and particles injected into the bed, only 18% of particles travelled greater than the median  
 509 distance between identical geomorphological units. By year, the proportions that did so were 7%, 23%,  
 510 and 25% of the 2010, 2011, and 2012 particles, respectively; examined by size-class, it was 38%, 17%,  
 511 6%, and 0% for the 22.3–32 mm, 32–45 mm, 45–64 mm, and 64–90.5 mm classes, respectively.  
 512 Moreover, for all dates and particles injected into the bed, only 37% of particles travelled a distance  
 513 longer than half the median distance between identical geomorphological units. Detailed by year, that  
 514 proportion was 21%, 46%, and 35% for the 2010, 2011, and 2012 particles, respectively. Examined by

515 size-class, it was 59%, 45%, 18%, and 2% for the 22.3–32 mm, 32–45 mm, 45–64 mm, and 64–90.5  
516 mm classes, respectively.

517 Finally, we also characterized the influence of the laterally migrating bar (B4) on the trapping  
518 efficiency of particles at a decadal scale. For each geomorphic unit of tag injection upstream of the most  
519 active bar (all dates, cluster and cross-section taken together), we looked at the percentage of particles  
520 trapped in that bar. The Figure 9 shows that whether it be for all particles or only for the 22.3–32 mm  
521 size-class, the percentage of particles trapped in the B4 bar strongly decreased along the 100–120 m  
522 upstream of it; however, the influence of that bar on particle trapping then becomes null between 220  
523 and 280 m upstream of it. Hence, the length scale of the bar B4's influence on bedload transport at a  
524 decadal period seems to not exceed 220–280 m. Furthermore, most particles injected at the bar head  
525 remained on the bar (92%). Finally, we looked at the percentage of 22.3–32 mm particles injected into  
526 the upstream active bank and at its toe that were deposited in the B4 bar. For particles in the bank, this  
527 bar trapped 36% of the tagged particles; for those at the bank toe, it trapped 44% of them. These values  
528 exceeded somewhat those reported for the particles injected in the surrounding geomorphic units (8%  
529 for S3, 25% for M3A, these located at the same cross-section as the cluster at the bank toe, and 33% for  
530 M3B).



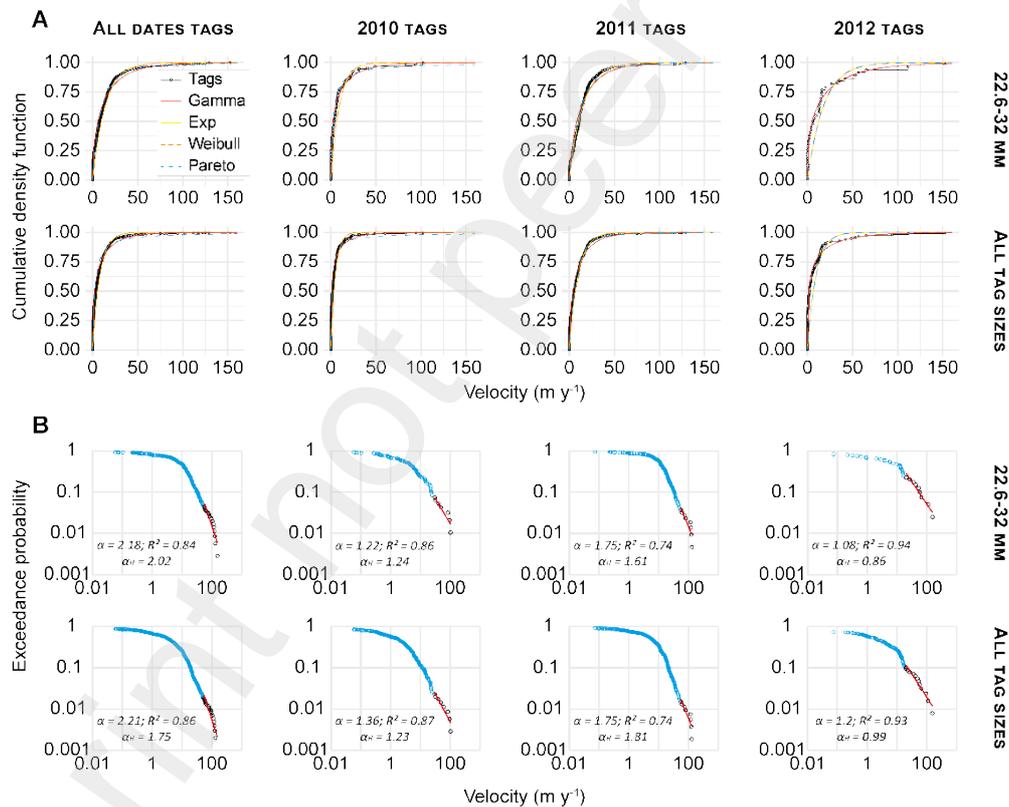
531  
532 Figure 9 – Percentage of particles trapped in the bar B4 in 2020 in relation to the distance from the  
533 injection point to the bar head.

#### 534 535 4.4 Velocity distribution

536 Whether we examine particles all together or by date of injection, the distribution of their path length  
537 was strongly right-skewed (Figure 10). The four probability distributions fitted—exponential, gamma,  
538 Pareto, and Weibull—described well the annual velocity distribution (Figure 10A). Based on the AIC,

539 the best fit was obtained by the Pareto distribution (Pareto type 2), except for the 2012 tags, where  
 540 gamma and exponential distributions appear better suited.

541 Finally, when the particles are differentiated by year of injection, the  $\alpha$  and  $\alpha_H$  values are  
 542 consistently  $< 2$ , indicating the strong likelihood of heavy-tail velocity distributions (for the 22.6–32  
 543 size-class:  $\alpha$  between 1.08 and 1.75 with an  $R^2$  of 0.74–0.94, and range of  $\alpha_H$  between 0.9 and 1.6; for  
 544 all particle sizes:  $\alpha$  between 1.12 and 1.75 with an  $R^2$  of 0.74–0.93, and range of  $\alpha_H$  between 0.99 and  
 545 1.81) (Figure 10B). When all years of injection are taken together, the discrimination between thin and  
 546 heavy tails was less clear in that most of  $\alpha$  and  $\alpha_H$  were slightly higher, even if relatively close, than 2  
 547 ( $\alpha = 2.12$ ,  $R^2 = 0.86$ , and  $\alpha_H = 1.75$  for the 22.6–32 size-class;  $\alpha = 2.18$ ,  $R^2 = 0.84$ , and  $\alpha_H = 2.02$  for  
 548 all particle sizes) (Figure 10B).

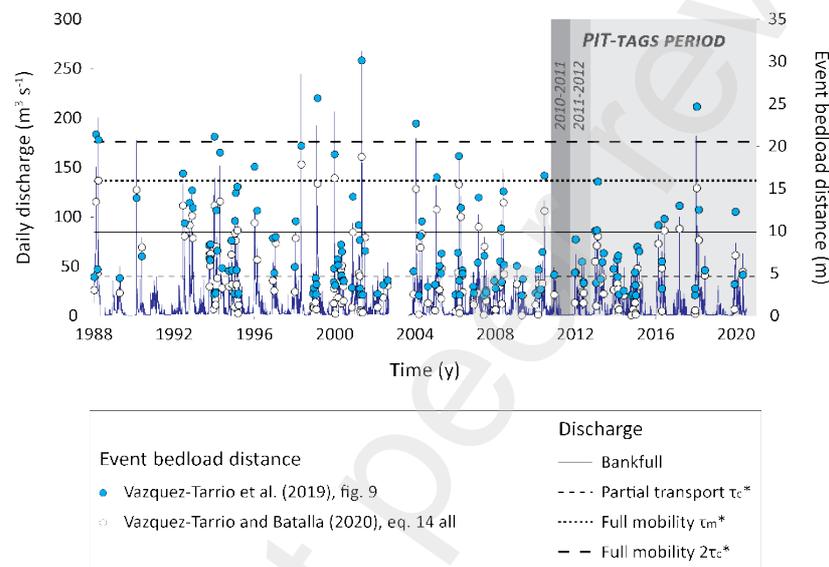


549 Figure 10 – Cumulative density function of annual velocities fitted with fitted exponential, gamma,  
 550 Pareto, and Weibull distributions (A); Exceedance probability plots of annual velocities with  $\alpha$  and  $\alpha_H$   
 551 values of the tail’s distributions (tails are plotted in black) (B).

552  
 553  
 554

555 **4.5 Estimation of event and long-term bedload velocity**

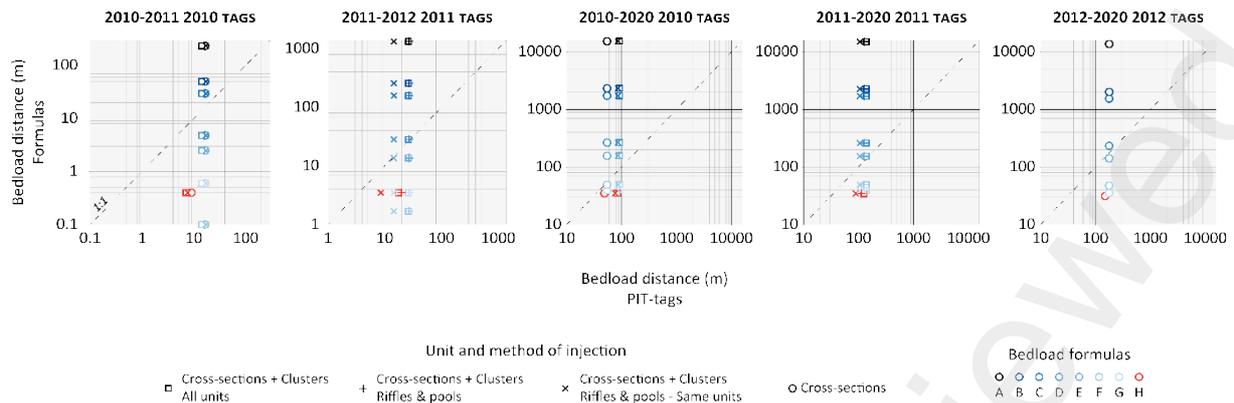
556 For the whole discharge record (1988–2020) at the reference gauging station of Montluçon, 154  
 557 competent events (50 events per decade) occurred, with a mean duration of 7 days per event (Figure  
 558 11). Full mobility is theoretically reached at  $137 \text{ m}^3 \text{ s}^{-1}$  and  $176 \text{ m}^3 \text{ s}^{-1}$  (corresponding to return intervals  
 559 of 3 years and 6 years, computed according Gumbel’s adjustment of annual maximum discharges) when  
 560 estimated from  $\tau_m^*$  and  $\tau_c^*$ , respectively (Figure 11). This happened for 14 and 9 events from 1988 to  
 561 2020, respectively (Figure 11).



562  
 563 Figure 11 – Reconstruction of the mean event bedload distances for  $D_{50}$  from 1988 to 2020.

564  
 565 Comparing the actual distance travelled by the bed  $D_{50}$  from tag tracking (22.6–32 mm size-  
 566 class) to that predicted by recent formulas in the literature shows a relatively good agreement for those  
 567 of figure 9 in Vázquez-Tarrio et al. (2019) (here, formula D in Figure 12Figure 11) and for all types of  
 568 rivers [eq. 14] in Vázquez-Tarrio and Batalla (2019) (here, formula D in Figure 12). This was verified  
 569 for annual transport distance in 2010–2011, though to a lesser extent than in other periods, namely 2011–  
 570 2012 and the longer periods of 2010–2020, 2011–2020, and 2012–2020 (Figure 12).

571



572

573 Figure 12 – Mean bedload distance (m) between 2010 and 2020 estimated using bedload formulas  
 574 (with critical discharge values of  $40 \text{ m}^3 \text{ s}^{-1}$  and  $50 \text{ m}^3 \text{ s}^{-1}$ ) and PIT-tags tracking. The distances were  
 575 obtained from mobilized and non-mobilized particles for all formulas, with the exception of formula H  
 576 that computes distances from mobilized particles only. In bold, the distances obtained from formulas  
 577 that are closest to the empirical tag distances. CSs: cross-sections. Cs: clusters.

578 A: Vázquez-Tarrío and Batalla (2019), eq. 13. B: Vázquez-Tarrío et al. (2019), eq. for riffle-pool rivers  
 579 in figure 4 for riffle-pool rivers. C: Vázquez-Tarrío et al. (2019), eq. in figure 2 for riffle-pool rivers  
 580 with width/depth bankfull ratio  $> 10$ . D: Vázquez-Tarrío et al. (2019), eq. for all rivers except the step-  
 581 pool ones of figure 9. E: Vázquez-Tarrío and Batalla (2019), eq. 14 for all rivers. F: Vázquez-Tarrío and  
 582 Batalla (2019), eq. 14 for riffle-pool rivers. G: Vázquez-Tarrío and Batalla (2019), eq. 15 for riffle-pool  
 583 rivers. H: Gilet et al. (2020), eq. 4.

584

585 These comparisons revealed that both formulas were well able to reconstruct the transport  
 586 distances of  $D_{50}$  at the competent event scale on the studied bend. Between 1988 and 2020, the mean  
 587 and median event distances for the 154 events that occurred were respectively 5.6 m and 7.7 m when  
 588 using the formula D, and likewise 3.3 m and 5.1 m when using formula E. Of all events, 90% had a  
 589 distance less than 12.2-15.7 m. The maximum distance was 18.8 m and 30.2 m under formula D and E,  
 590 respectively, being equal or lower than the active channel width and 5.9–3.6 times lower than the median  
 591 distance between riffles and between pools. The maximum distance attained was for a 31-day-long  
 592 event, whose discharge was the highest during the study period (with a 34-year return interval period,  
 593 computed according Gumbel's adjustment of annual maximum discharges) and for which the ratio

594  $\tau^*/\tau_c^*$  was equal to 2.3. Not one of the 9–14 events for which full mobility occurred was thus able to  
595 transport bedload on a distance equivalent to the distance between identical successive geomorphic  
596 units. Even when applying the formulas to a fictional 10-day duration event with a constant 100-year  
597 return interval discharge ( $321 \text{ m}^3 \text{ s}^{-1}$ ) yielded very low distances: 22 m for formula D and 20 m for  
598 formula E. Finally, extrapolating the cumulative distance obtained for the 1988–2020 period to a  
599 duration of one century yielded an average long-term velocity of 2.5–3.8 km century<sup>-1</sup>.

600

## 601 **5. Discussion**

### 602 **5.1 Variability in bed mobility and bedload velocity according to the year, type of** 603 **geomorphic unit, or method of injection**

604 Our results show there is important variability in both bed mobility and bedload velocity according to  
605 the year, geomorphic unit type (and between units of the same type), and injection method (in cluster or  
606 along cross-section) Understanding the reasons for such a discrepancy is a crucial issue in the context  
607 of trying to obtain reliable bedload velocities.

608 Regarding the variability between particles injected in riffles versus pools, this could arise from  
609 a difference in the available energy between these two types of units. According to the concept of  
610 hydraulic reversibility, the average velocities and shear stresses during high flow should be higher in  
611 pools (Booker et al., 2001; Caamano et al., 2009; Keller, 1971; Keller and Florsheim, 1993; Lisle, 1979;  
612 MacWilliams Jr. et al., 2006; Milan et al., 2001; Petit, 1987; Thompson, 2011; Thompson et al., 1999).  
613 Yet that process is not universal: it may only occur when the wetted cross-sectional area of riffles  
614 exceeds that of pools (Carling, 1991; Clifford and Richards, 1992; Milan, 2013; Milan et al., 2002;  
615 Thompson, 2011; Wilkinson et al., 2004), a situation rather infrequent (Carling and Wood, 1994;  
616 Thompson, 2011; Thompson et al., 1999). For example, from a set of 702 pool-riffle couplets across  
617 northern California, Byrne et al. (2021) found that reversal occurs at the bankfull for only 18% of all  
618 couplets. The higher mobility of material in pools is perhaps more likely the result of the existence at  
619 high-flow of convergent and jet flow at the entrance and centre of pools, respectively, and of divergent  
620 and uniform flow at the pool tail and in riffles, respectively (e.g., MacWilliams Jr. et al., 2006;

621 Thompson and MacVicar, 2020). Furthermore, bed mobility and velocity could be promoted for tracers  
622 injected into forced pools, namely for four of the seven pools equipped in our study (i.e., P1B, P2B,  
623 P3A, P3B). In such units, the constriction imposed by the crosswise physical obstacles reinforced the  
624 convergence of flows, and in such circumstances the flows near the bed surface are generally associated  
625 with high turbulence (Hassan and Woodsmith, 2004; MacVicar and Roy, 2007a, 2007b, 2011;  
626 Thompson, 2007; Thompson and Wohl, 2009). When tracers are injected in the deepest sections of the  
627 forced pools, as done in our study, mobility is reportedly higher than in riffles (Thompson and Wohl,  
628 2009; MacVicar and Roy, 2011). Yet our data do not show such an effect of forced pools: for each pair  
629 of unforced–forced pools (M1A–M1B, M2A–M2B, M3A–M3B), the velocity was either higher or  
630 similar for particles injected in the unforced pool. The difference between forced and free-formed pools  
631 could nonetheless result from lower distances travelled through pools for particles injected in the former  
632 (24 m, 38 m, and 21 m from the injection point to the exit of the forced pools M1B, M2B, and M3B,  
633 respectively, versus 103 m, 87 m, and 69 m for the free-formed pools M1A, M2A, and M3A,  
634 respectively). Furthermore, the lateral location of clusters can also explain, at least in part, the difference  
635 in bed mobility and bedload velocity observed between riffles and pools. Whereas clusters in pools were  
636 systematically located in their central deepest section, where the jet flow is supposed to occur, three  
637 of the five riffle clusters (R2, R3, and R5) were located in the bend and not at the inflexion point (R1  
638 and R4), where the clusters were positioned rather than in the inner half of the bed, where the flow  
639 velocity could be relatively low. This explanation is supported by the clearly lower bed mobility and  
640 bedload velocity of tracers injected in these three riffles compared with the two remaining riffles (range  
641 of mobilization rate: 7%–72% for R2, R3, and R5 versus 93%–100% for R1 and R4; respective ranges  
642 of mean, median velocity: 0.8–4.9 m y<sup>-1</sup>, 0–0.3 m y<sup>-1</sup> versus 3.8–8.2, 0–0.3 m y<sup>-1</sup> and 3.2–6.8, 0–0.3 m  
643 y<sup>-1</sup>). When compared with pools, the mobilization rate as well as bedload velocity of these three riffles  
644 (R2, R3, R5) are also clearly lower, but similar for the two remaining riffles. In addition,  
645 sedimentological arguments can also be put forward. Some research demonstrated that the structure of  
646 the surface layer of pools (their degree of packing especially) is clearly less stable than for riffles (e.g.,  
647 Clifford, 1993; Hodge et al., 2013; Sear, 1996). Further, during low flow, the competence in riffles  
648 surpasses that in pools (Milan et al., 2002): the finest fraction of the bedload, sand, and small gravel, is

649 at least partly exported from the former and accumulated in the latter (Jackson and Beschta, 1982; Lisle  
650 and Hilton, 1992, 1999; Milan, 2013; Sear, 1996). The pools are thus frequently lined with a more or  
651 less thick layer of fine material and the sand content in their subsurface layer could be more important  
652 than in riffles. This may have been a factor contributing to greater bed mobility in pools (Sear, 1996;  
653 Vahidi et al., 2020). Work by Curran and Wilcock (2005), Wilcock (1998) or Wilcock and Crowe  
654 (2003), for example, show that significant increases in the mobility of gravel occur when the proportion  
655 of sand in the bed increases. All the possible explanations presented above are theoretically valid at the  
656 scale of the competent events, or so long as tracers remain in their unit of injection. Over time, given  
657 the tracers' alternating passage through riffles and pools, the discrepancy in velocity should eventually  
658 slow to zero. When considering only those tracers that left their unit of injection, we still found a marked  
659 difference in bedload velocity between tracers seeded in riffles and in pools: for 2010 tracers, mean  
660 (median) of 11 (5.6)  $\text{m y}^{-1}$  and of 9.6 (6.7)  $\text{m y}^{-1}$  for riffles and pools, respectively; for 2011 tracers,  
661 mean-median of 8.1 (6.3)  $\text{m y}^{-1}$  and 13.7 (12.6)  $\text{m y}^{-1}$  for riffles and pools, respectively. This shows that  
662 the effect on the bedload velocity from the type of unit that received the injection can persist 10 years  
663 after the injection. This most likely arose from the low bedload velocity reported: half of the tracers  
664 remained in their unit of injection (31% for the 22.6–32 mm size-class) and 80% of tracers were  
665 deposited in their unit of injection or in the downstream one (62% for the 22.6–32 mm size-class) (Figure  
666 7). Secondly, it is also probably reflects the effect from the difference in distance from injection points  
667 to the exit of a geomorphic unit according to its type. This distance is clearly shorter in riffles than pools;  
668 mean (median) of 21 (15) m versus 62 (69) m, and references back to the proportions leaving the two  
669 types of units. However, lacking detailed data on the hydraulic functioning and surface sediment  
670 structure of these units, which of the above potential explanations—for the difference in velocity  
671 between particles injected in riffles versus pools—is prominent cannot be known.

672 The lower velocity of particles injected as clusters than along cross-sections likely originates  
673 from the bed mobility's laterally discrete nature. For partial transport events, namely for most of the  
674 competent events, only a portion of the bed cross-section, which expands with the flow strength, is  
675 indeed mobile (Ferguson, 2003; Frings and Vollmer, 2017; Haschenburger, 2017; Haschebburger and  
676 Wilcock, 2003; Papangelakis and Hassan, 2016). Injections performed in a cluster would thus provide

677 an under-estimation of the bedload velocity when the cluster is positioned on a rarely active portion.  
678 Conversely, that velocity could be overestimated if the cluster is located on a frequently active part of  
679 the bed. Broadly then, injecting along a cross-section would let us incorporate the lateral variability of  
680 bed mobility and thus yield a more representative image of bedload velocity.

681 In order to integrate the effects of these different sources of variability for bed mobility—that is  
682 laterally, between types of geomorphic units, as well as between units of the same type)—thereby obtain  
683 the most reliable bedload velocity possible, we recommend using seed tracers in several equidistant  
684 clusters along cross-sections, with a least two or three particles of each half-phi grain-size per cluster.  
685 Such injections should be made in several riffles and in several pools, with cross-sections systematically  
686 located at the same relative longitudinal position (i.e., heads of riffles and centres of pools, for example).  
687 Whatever the chosen injection design, the variability in bedload velocity should lessen over time and be  
688 paramount when full mobility is rare.

689 The inherent spatial variability of bed mobility and velocity could also explain, in part, the lower  
690 mobility and velocity observed for 2010 tags vis-à-vis 2011 and 2012 to the extent that particles were  
691 injected at a slightly different position in a given year versus others. Operator bias is very likely  
692 negligible, in that particles were injected in the same way and by the same person. The last potential  
693 explanation is related to the differing flow history between tracers: because 2010 and 2011 tracers share  
694 the same hydrology following the injection of 2011 tracers, an explanation for the lowest decadal  
695 velocity of the 2010 tracers could theoretically lie in what happened before the injection of the 2011  
696 tracers. Indeed, the 2010 tracers underwent a very long low flow period prior to the 2011 tracers'  
697 injection (Figure 11), that could generated a rearrangement of the surface structure that led to its  
698 strengthening, thus limiting the particles' mobility. Numerous authors have highlighted the fundamental  
699 role of stress history, that is to say sub-critical shear stresses, in strengthening the surface layer stability  
700 (Haynes and Pender, 2007; Monteith and Pender, 2005; Ockelford and Haynes, 2013; Paphitis and  
701 Collins, 2005). The effect of such limitations for the 2010 tracers' mobility should have emerged in the  
702 2010–2020 period, and accordingly, in 2011–2012, the 2010 tracers ought to have moved slower than  
703 the 2011 tracers. Yet the opposite occurred. When comparing tracers introduced in clusters to the same  
704 units (pools or riffles) in both years, the mean velocity of the 22.6–32 mm size-class is  $12.9 \text{ m y}^{-1}$  and

705 5.4 m y<sup>-1</sup> for the 2010 and 2011 tracers, respectively. Further, whereas the total expenditure of flow  
706 energy for a discharge higher than the critical discharge (*sensu* Haschenburger, 2011a) was 9.4 times  
707 lower in 2010–2011 than 2011–2012, the mean virtual velocity (distance divided by the duration of  
708 competent discharge) of the 22.6–32 mm size-class was clearly higher for the 2010 tags in 2010–2011  
709 than the tags 2011 in 2011–2012 (69.4 mm h<sup>-1</sup> versus 7.3 mm h<sup>-1</sup>). We conclude the difference in the  
710 location of the tracers' injection between years is the only satisfactory explanation for the variability in  
711 velocity between years.

712

## 713 **5.2 Interactions between event bedload distances and bedforms**

714 For the entire period of recorded discharge (1988–2020), despite the occurrence of 9–14 events for  
715 which the full mobility was reached, the maximal estimated mean event distance for the D<sub>50</sub> was 30.2  
716 m. This is roughly equivalent to the active channel width and 3.6 times less than the median distance  
717 between riffles and between pools. The main implications for the Cher River, and perhaps more broadly  
718 for temperate low-energy gravel-bed rivers, are twofold. First, event transport distances would be  
719 always, or almost always, shorter than the distance between two successive identical geomorphic units.  
720 It implies that trapping effect by bars would be rare, or even absent, at the scale of competent events for  
721 most of particles located at a distance higher than an active channel width. Second, since no event is  
722 able to transport bedload on distances at least equal to the length of a single riffle-pool unit, the  
723 maintenance of bedforms, and especially that of bars, would thus become disconnected from the event  
724 transport distances or would depend on successive minor changes. Therefore, the model proposed by  
725 Pyrcce and Ashmore (2003) would not be universally valid. When computing the cumulative distance of  
726 D<sub>50</sub> for events whose peak is higher or lower than the bankfull discharge, we see that events below the  
727 bankfull are responsible for about half of the total distance for the 1988–2020 period. By setting the  
728 threshold to a 2-year return interval flood, events with lower discharge than that are responsible for ca.  
729 70% of the total distance for the 1988–2020 period. This agrees with and supplements the findings of  
730 Dépret et al. (2015) along the same reach on which the study bend is located, showing that its  
731 morphogenesis, from the perspective of planform mobility and effective discharge for the bedload, is  
732 chiefly controlled by low-magnitude hydrological events (< 2 years RI).

733 Finally, the possibility remains that the study bend's current bed morphology could be  
734 maintained by very rare floods and/or had been inherited from a past flood regime. Still, along those  
735 scarce sections of the Cher River whose geometry has freely adjusted over the last decades (due to the  
736 lack of lateral constraints), there exists riffle–pool–bar sequences with length scales of bedforms similar  
737 to that in the study reach. This suggests the present morphology can be maintained under the current  
738 flood regime, and without the occurrence of a very rare flood event.

739

### 740 **5.3 Long-term bedload estimation**

741 The range of long-term bedload velocity we proposed here is an overestimate for two key reasons. First,  
742 the study bend's hydraulic parameters are not representative of the whole 12-km long reach, which ends  
743 at the junction with the Aumance River (see Dépret et al., 2015, 2017 for details) and is where the bend  
744 is located. Although their active channel width is similar, the low-flow bed slope is equal to 0.00063 m  
745 m<sup>-1</sup> along the reach, versus the greater 0.0011 m m<sup>-1</sup> along the study bend, where the bankfull stream  
746 power is thus almost two times higher (30 W m<sup>-2</sup> versus 17 W m<sup>-2</sup>). This implies the long-term velocity  
747 should be derived instead from the hydraulic parameters of the reach. By doing so, the application of  
748 formulas D and E using hydraulic parameters of the reach provides velocities of 0.95 and 1.3 km century<sup>-1</sup>,  
749 respectively (versus 3.8 and 2.5 km century<sup>-1</sup> for the study bend). Secondly, it is very likely that our  
750 estimation takes into account, only partially, the progressive slowdown of the tracers resulting from their  
751 mixing within the event active layer (*sensu* Church and Haschenburger, 2017), or their trapping in bars  
752 or in the floodplain (Ferguson et al., 2002; Ferguson and Hoey, 2002; Haschenburger, 2011a, 2011b;  
753 Houbrechts et al., 2015; Iwasaki et al., 2018; Pelosi et al., 2016). For example, in the Carnation Creek,  
754 Haschenburger (2011a) reported that a 72% reduction in velocity after a few years, which reached then  
755 an asymptotic value. In the Allt Dubhaig, Ferguson et al. (2002) found a 50% reduction in velocity when  
756 comparing it 2 years and 8 years following the tracer injection. Here, long-term bedload velocity in the  
757 Cher River was estimated through formulas that succeeded in reconstructing the tracers' velocity at a  
758 10-year scale. Yet, because of the low transport distances reported, we find that only a small proportion  
759 of all tracers could have been affected by the trapping effect of bars on this time scale. Such a weak  
760 effect is also evident in the similar velocity of tracers deposited on and outside the bar B4: respectively

761 having a mean (median) of 8 (5.3) and 8.1 (3.8)  $\text{m y}^{-1}$  for all particles; likewise, 13.6 (8.7) and 14.7 (10)  
762  $\text{m y}^{-1}$  for the 22–32 mm size-class. Furthermore, especially because of relatively weak hydrologic  
763 activity during the 10-year study period, coupled with river’s inherently low energy, it is likely that the  
764 mixing process of tracers into the active layer was still incomplete at 10 years since their injection. In  
765 this respect, Haschenburger (2011a) showed, for example, that large floods accelerate the rate at which  
766 the vertical mixing of surface tracers occurs. Recently, Vázquez-Tarrío et al. (2021) highlighted that, at  
767 the event scale, the ratio between the Shields stress for the peak flow and the critical Shields stress is  
768 one of the main drivers of the active layer’s depth. By comparing the virtual velocity (i.e., total distance  
769 divided by the total duration of competent events) of tracers 1 year and 10 years following their injection,  
770 we could indirectly gain insight into the intensity of their mixing process, the idea being that the smaller  
771 the difference, the weaker is the mixing. For the 2010 tracers, the mean virtual velocity of the 22.6–32  
772 mm size-class was much faster in the 2010–2011 period than 2010–2020 period ( $74 \text{ mm h}^{-1}$  versus  $13$   
773  $\text{mm h}^{-1}$ , a 82% decrease). Yet, when comparing the median velocity, the velocity is higher for the longest  
774 period ( $5 \text{ mm h}^{-1}$  versus  $3 \text{ mm h}^{-1}$ , a 148% increase). We find a similar tendency for the 2011 tracers,  
775 but with a clearly smaller difference for the mean ( $24 \text{ mm h}^{-1}$  for the 2011–2012 period versus  $20 \text{ mm}$   
776  $\text{h}^{-1}$  for the 2011–2020 period, a 15% decrease; for the median,  $8 \text{ mm h}^{-1}$  versus  $15 \text{ mm h}^{-1}$ , a 198%  
777 increase). Hence, it seems virtual velocity has not or only marginally decreased with elapsed time. This  
778 would tend to confirm a weak mixing of tracers in the active layer. The right-skewed distribution of the  
779 bedload velocity and its likely heavy-tail (Figure 10) further support this interpretation of a mixing  
780 having yet not reached its equilibrium. Both features, which could serve as a signature of a super-  
781 diffusive regime of the bedload (Lajeunesse et al., 2013), would stem from the fact that a crucial  
782 proportion of them remains overly mobile so long as they have not been fully mixed into the active layer  
783 (Pelosi et al., 2016; Pierce and Hassan, 2020; Wu et al., 2019; Zhang et al., 2012). On a longer time-  
784 scale, after the mixing has been achieved, the dispersion regime of the tracers would tend to become  
785 diffusive, rendering their distribution of velocities more normal, with their variance increasing linearly  
786 with time and their velocity becoming asymptotic (Guillon, 2016; Lajeunesse et al., 2018; Wu et al.,  
787 2019; Zhang et al., 2012). But there is no consensus yet concerning the anomalous or normal character  
788 of the dispersion of tracers in the long-term. Accordingly, Pierce and Hassan (2020) suggested that on

789 long time-scale—a geomorphic range as they called it—the regime would remain anomalous, for which  
790 superdiffusion or subdiffusion happens in a way that depends on the long-time decay of the exhumation  
791 time distribution of buried particles.

792

## 793 **6. Conclusion**

794 This paper focused on characterizing the variability of bed mobility in a low-energy, gravel-bed  
795 meandering river, with particular attention paid to the relationship between bed transport distances and  
796 bed forms. Our combined analysis of 10-years of data for tracked PIT-tags and a 32-year reconstruction  
797 of bedload distance events during which full mobility was reached on several occasions reveals a  
798 substantial slowness of the bedload in the studied river. Our findings highlight two take-home messages.

799 First, the trapping effect by bars is rare, or even absent, at the scale of competent events for most of  
800 particles located at a distance greater than an active channel width from the bar. Second, since no event  
801 is able to transport bedload over distances at least equal to the length of one riffle-pool unit, the  
802 maintenance of bedforms, and especially of bars, would be disconnected from the events' transport  
803 distances or would result from successive minor changes. These findings do not support the hypothesis  
804 of Pyrcce and Ashmore (2003a, 2005) claiming that, for full mobile events, bedload should be transported  
805 on distances at least equal to the distance between two successive bars, equivalent to the length of a  
806 riffle-pool unit, and that bedform maintenance depends on such events. More field and flume  
807 experiments should now be undertaken to check our results and to better understand the suite of  
808 conditions allowing the coexistence of an active, well-developed riffle-pool-bar morphology and low  
809 bedload distances during full mobility events.

810 Further, we uncovered evidence for considerable decadal-scale variability in the bedload  
811 velocity obtained from tracers according to the year of injection, the type of geomorphic unit that got  
812 injected, or the method of injection (cluster or cross-section). This emphasises why it is imperative to  
813 systematically consider the moment, location, and way tracers are seeded for the sound inference and  
814 interpretation of bedload velocity. In addition to exemplifying the well-known strong spatiotemporal  
815 variability of bedload processes, our results also highlight persistent effects upon velocity estimation  
816 from where, when and how tracers are injected, especially for low-energy rivers.

817 Lastly, our PIT-tags survey provides new empirical data on the long-term dispersion of surface  
818 seeded tracers at the decade temporal scale, this rarely documented in the literature, even less for low-  
819 energy rivers (Bradley, 2017; Haschenburger, 2011a, 2013; McDowell and Hassan, 2020; Papangelakis  
820 and Hassan, 2016). The right-skewed and heavy tailed velocity distribution reported here could indicate  
821 a very incomplete mixing of tracers within the active layer. The vertical diffusion of tracers in such low-  
822 energy rivers could therefore clearly be a more time-consuming process than previously reported for the  
823 few rivers documented to date (Haschenburger, 2011b, 2012). Consequently, the long-term bedload  
824 velocity estimation we gleaned from the PIT-tags data and bedload formulas should be viewed as  
825 strongly overestimated. This pinpoints the difficulty in (1) obtaining robust information on the way of,  
826 and velocity at which, the processes of advection-diffusion of the bedload occur in the long-term; and  
827 (2) extrapolating to long-term velocities from the PIT-tags velocities recorded over just a few years.

828

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833

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