

# Particle transport in gravel-bed rivers: revisiting passive tracer data

Q2 Q1 Daniel Vázquez-Tarrió,<sup>1,2\*</sup>  Alain Recking,<sup>3</sup> Frédéric Liébault,<sup>3</sup> Michal Tal<sup>4</sup> and Rosana Menéndez-Duarte<sup>2</sup>

<sup>1</sup> INDUROT, Universidad de Oviedo, Campus de Mieres, s/n 33600, Mieres, Spain

<sup>2</sup> Departament of Geology, Universidad de Oviedo, c\ Jesús Arias de Velasco, s/n 33005, Oviedo, Spain

<sup>3</sup> University Grenoble Alpes, Irstea, UR ETGR, St-Martin-d'Hères, France

<sup>4</sup> Aix Marseille University CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France

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\*Correspondence to: D. Vázquez-Tarrió, INDUROT, Universidad de Oviedo, Campus de Mieres, s/n 33600, Mieres, Spain. E-mail: vazquezdaniel@uniovi.es

# ESPL

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**ABSTRACT:** Data from tracer experiments were compiled and analysed in order to explore the role of geomorphological, hydrological and sedimentological constraints on fluvial gravel transport in gravel-bed rivers. A large data set from 217 transport episodes of tagged stones were compiled from 33 scientific papers. Our analyses showed that while magnitude of peak discharge is a major control on gravel transport and mobility, tracer travel distances show some scale dependence on the morphological configuration of the channel. Our results also highlight differences in the way tracers are displaced between step–pool and riffle and pool channels. The riffle–pool sequence seems to be a more efficient trap for travelling gravels than the step–pool pair. In addition, in step–pool channels there are clear differences in tracer transport between observations of first displacements after tracer seeding (unconstrained-stone conditions), and second and subsequent observations of tracer displacements (constrained-stone conditions). The comparison between tracer experiments under constrained conditions and those under unconstrained conditions also highlights the importance of bed state and structures in gravel mobility. The results of this study confirm that sediment transport in gravel-bed rivers is a complex process, whereby sedimentological and geomorphological controls are superimposed on the hydraulic forcing. © 2018 John Wiley & Sons, Ltd.

**KEYWORDS:** bedload transport; sediment dispersion; gravel-bed rivers; tracers

## 1. Introduction

Sediment tracking using tagged stones placed in the streambed represents an interesting and relatively inexpensive source of information on sediment transport and dispersion in gravel-bed rivers. In this regard, tagged stones have been used to study flow competence and grain position relative to meso- and micro-bedforms (Laronne and Carson, 1976), particle entrainment (Hassan *et al.*, 1992), constraints on sediment dispersion (Church and Hassan, 1992), virtual rates of sediment movement (Hassan *et al.*, 1991), the distribution of periods of rest and movement during transport episodes (McNamara and Borden, 2004), the relationship between gravel dispersion and channel morphology (Milan *et al.*, 2002; Milan, 2013b; Papangelakis and Hassan, 2016), sediment volumes carried during floods (Liébault and Laronne, 2008; Vázquez-Tarrió and Menéndez-Duarte, 2014, 2015), bed material/bedload exchanges (Hassan and Church, 1994), and scour and fill depths (Haschenburger, 1999). According to Haschenburger (2013), similar observations cannot be collected using only laboratory flumes. Earlier tags consisted of painted stones (Laronne and Carson, 1976), inserted magnets (Hassan *et al.*, 1984) or magnetically enhanced gravels (Sear, 1996). The recently developed method of inserting passive integrated transponders (PIT tags) into clasts and tracking them with a radio antenna

(Nichols, 2004; Lamarre *et al.*, 2005; Lamarre and Roy, 2008b; Schneider *et al.*, 2010; Bradley and Tucker, 2012; Liébault *et al.*, 2012; Olinde and Johnson, 2013; Phillips *et al.*, 2013), has reduced some of the problems associated with previous passive tracer techniques, including low recovery rates and the problem of buried tracers and decaying labels (Hassan and Bradley, 2017). More recently, active tracking methods have been shown to be very promising in terms of expanding the tracer method to larger river systems than those typically studied with passive tracers (Cassel *et al.*, 2017). Owing to these advances, sediment tagging has become a common technique in geomorphological studies.

The particle tracing method enables tracking the movement of individual stones on the streambed. Indeed, it is the only suitable field method providing information about particle paths and patterns of bedload dispersion in natural streams. One of the most widely explored issues using tracers has been the downstream displacement of fluvial gravels (Church and Hassan, 1992; Haschenburger, 2011). Several studies have used tracer data in order to establish functional relationships between tracer travel distances and flow magnitude (Hassan *et al.*, 1991; Schneider *et al.*, 2014; Houbrechts *et al.*, 2015). Other studies (Milan *et al.*, 2002; Pyrcz and Ashmore, 2003a, 2003b, 2005; Liébault *et al.*, 2012; Milan, 2013b) have examined the control exerted by macroforms and channel

morphology on tracer dispersion in bar–pool channels. In the same vein, a recent study by Papangelakis and Hassan (2016) analysed the role played by different channel morphologies in tracer displacement in the gravel-bed East Creek (Canada) using a 10-year tracer data set. In addition, re-examination of compiled tracing data highlighted relationships between tracer travel distance and grain size, duration of competent flow and tracer dispersion, dispersal velocity and excess stream power, mean travel distances and flow magnitude, and the distributions of travel distances and burial depths (Hassan *et al.*, 1991; Church and Hassan, 1992; Hassan and Church, 1992; Haschenburger, 2013; Milan, 2013a). Hassan and Bradley (2017) also stated the constraining effect played by bed texture and particle arrangements on particle displacement.

These previous studies helped establish hydraulics as a major forcing on fluvial gravel transport. However, an important amount of variance in available tracer data remains unexplained (Hassan and Bradley, 2017), suggesting the influence of controls other than flow magnitude on tracer displacement, for example bed state or channel morphology (Papangelakis and Hassan, 2016; Hassan and Bradley, 2017). However, the function played by sediment texture and channel morphology on bed sediment transport is difficult to quantify using only the results from a single tracer experiment due to the complex interactions between bed morphology, surface sediment and flow (Hassan and Bradley, 2017). The goal of this study was to investigate hydraulic, textural, and geomorphological constraints on downstream transport of fluvial gravels using a sufficiently large data set that would permit us to discuss and compare data from a wide diversity of mountain rivers. In order to do this, we compiled and analysed a large data set based on 217 passive tracer experiments reported in 33 previously published studies.

In-depth reviews of the gravel tagging have been published by Sear *et al.* (2000), Hassan and Ergenzinger (2003), Hassan and Roy (2015) and Hassan and Bradley (2017). The present study presents novel analyses of data not considered in the previous studies. First, in order to improve our understanding of links between channel style and sediment transport in gravel-bed streams, we relate tracer travel distances to average spacing between morphological units (e.g. step–pool, bar–bar, pool–pool spacing in each case). In this sense, Beechie (2001) already observed an association between travel distance and channel width in tracer studies, suggesting that channel width appears to drive tracer transport as far as it also controls bar spacing. Later, Pyrce and Ashmore (2003a, 2003b, 2005) showed how during channel-forming flows in gravel-bed rivers, the path length of transported particles must be equal to the morphological length scale of the channel. Milan *et al.* (2002) and Milan (2013b) reported that channel morphology in pool–riffle channels influenced travel paths of tagged stones while Gintz *et al.* (1996) and Lamarre and Roy (2008b) investigated the role of step–pool morphology in gravel transport. Other works also showed how mean distance of travel of tracer stones is controlled by the average spacing of macroforms (Hassan *et al.*, 1991; Liébault *et al.*, 2012). Recently, Recking *et al.* (2016) also identified differences between bedload transport in different channel settings and suggested a ‘morphological imprint’ of bedload processes and thus an interest in studying the links between channel morphology and particle pathways in mountain rivers. In this present study, we explore the relationship between channel style and sediment displacement in detail, with a particular focus on differences between riffle and pool and step–pool channels. We also consider separately data of tracer displacements immediately after tracer seeding, referred to as ‘unconstrained-stone’ experiments, and data from second and subsequent tracer displacements, wherein tagged stones are considered to be ‘constrained’ by

bed structures (herein referred to as ‘constrained-stone’ experiments). Brayshaw *et al.* (1983), Reid *et al.* (1992), Powell and Ashworth (1995) and Church *et al.* (1998) pointed to the control of particle arrangements and clusters on entrainment of individual tracer particles. In addition, Church and Hassan (1992) and Hassan *et al.* (1992) highlighted the difficulty of isolating the size–distance problem from particle entrainment in tracer experiments where tagged stones are constrained in the bed. However, to our knowledge, no explicit comparison between these two different experimental conditions has been made in preceding assessments of tracer data. Finally, we analysed the fraction of mobile tracers and how it evolved with flow magnitude and duration. By considering the fraction of mobile tracers together with the analysis of tracer travel distances, we sought to maximize the information that could be obtained from available tracer data with respect to two of the main controls on bedload transport: surface bed mobility and downstream transport of river bed gravels.

This study builds on our understanding of the geomorphologic and hydrological controls on sediment transport and contributes in two important ways to the previous reviews of tracer studies cited earlier. One is the explicit comparison between ‘constrained-’ and ‘unconstrained-’ stone experiment conditions, which provides interesting insights into the influence of different channel morphologies on the way tracer stones are conveyed downstream in steep, mountain channels. The other concerns the analysis of the influence of antecedent, sub-threshold flow on tracer dispersion.

## 2. MATERIALS AND METHODS

### 2.1. Data set compilation

The data set used in this paper is comprised of results from 217 passive tracer experiments carried out in 30 gravel-bed rivers in various locations and published in 33 scientific papers between 1970 and 2016 (Table I). Data are derived from field experiments using painted, magnetically and PIT tagged stones. They cover a wide range of channel styles, morphologies and bed textures. The data come from studies spanning a wide range of hydrological regimes, from ephemeral streams in arid regions to perennial streams with gradually varied glacio-nival hydrological regimes.

We compiled the following information for each of the data sets: (a) general information describing the study reaches (channel width, channel slope, channel morphology, grain size of surface sediment, hydrological regime); (b) information about the tracer experiments (tracing method, peak discharge of the studied transport episodes, recovery ratios, percentage of mobilized particles, mean and maximum travel distances); (c) information on flow duration of the transport episodes (including number of peaks of flow) and the number of antecedent days, where available; and (d) whether the data was from first (unconstrained) displacements or second or later (constrained) displacements after tracer seeding. For the unconstrained data, special care was taken to only consider the actual data from first displacements after tracer seeding. Some studies did not report these first tracer movements in order to allow particles to become incorporated into the bed structure. In such cases, the first reported movements were obviously classed as constrained data.

Some of the above information was explicitly mentioned in the papers; and some could be inferred from graphs and figures (Table I). The compiled data was grouped by channel style: riffle and pool (RP), step–pool (SP), plane-bed (PB) and multithread (MT) channels (Montgomery and Buffington, 1997).

**Table 1.** Sources of data and information about the experiments compiled for this study

Stream	Source	Q <sub>bf</sub> (m <sup>3</sup> /s)	Channel slope	D <sub>50</sub> (mm)	Tagging method	Recovery ratio (%)	Travel distance (m)	Available information		
								Transport distance by grain size	Flow duration	Antecedent periods
Dry Creek (USA)	Keller (1970)	-	-	-	Painted	30-48.5	44.5-65.2	No	Yes (graphs)	Yes (inferred from graphs)
Seale's Brook (Canada)	Larone and Carson (1976)	-	0.05	100	Painted	3.1 - 6.7	53-112	Yes	Yes (graphs)	Yes (inferred from graphs)
White Clay Creek (USA)	Leopold and Emmett (1981)	-	-	58	Painted	-	10-50	No	No	No
Horse Creek (USA)	Butler (1977)	-	0.0037	40	Painted	85.7	84	Yes	No	No
Nahal Ebron (Israel)	Hassan <i>et al.</i> (1984); Hassan (1990)	-	0.016	56	Magnets	80-93	0-65.3	Yes	No	No
Alt Dubhaig (Scotland)	Ashworth (1987)	6.1	0.021	71	Painted	-	10-22	Yes	Yes (graphs)	Yes (graphs)
Nahal Og (Israel)	Hassan (1990) Schmidt and Ergenzinger (1992); Gintz <i>et al.</i> (1996)	-	0.014	35	Magnets	55	14.2-145.8	Yes	No	No
Lainbach (Germany)	Sear (1996)	30.0	0.02	120	Iron/Magnets	17-100	4-274	No	Yes (table)	Yes (inferred from table)
North Tyne (UK)	Haschenburger and Church (1998)	167.0	0.0018	54	Painted	38-68	1-87.8	Yes	Yes (table)	No
Carnation Creek (Canada)	Nichols (2004)	-	0.0056-0.012	47	Magnets	8.7-93.4	25.8-129.1	No	Yes (table)	No
Walnut Gulch (USA)	Rollet (2007)	-	0.029-0.036	-	PIT tag	96	-	No	No	No
Ain River (France)	Carré <i>et al.</i> (2007)	40.0	0.0013	46-118	PIT tag	25-36	26-43	Yes (graphs)	No	No
Nicolet river (Canada)	Dudley (2008)	21.0	-	90	PIT tag	97	3-97	No	No	No
Woodbrook creek	Camenen <i>et al.</i> (2010)	-	0.033	24	Magnets	81-98	0.1-2.5	Yes	Yes (table)	Yes (inferred from graphs/table)
Arc River (France)	Rollet <i>et al.</i> (2008)	-	0.006	73	PIT tag	12-80	6-66	Yes (graph)	Yes (inferred from graphs)	Yes (inferred from graphs)
Moras Creek (Canada)	Lamarre and Roy (2008)	-	0.012	60	PIT tag	87	>500 (max)	No	Yes (inferred from graphs)	No
Spruce Creek (Canada)	MacVicar and Roy (2011)	2.0	0.14	90	PIT tag	57-92	1.5-8.3	Yes (graphs)	Yes (table)	Yes (inferred from graphs)
Moras Creek (Canada)	Liébault <i>et al.</i> (2012); Chapuis (2012); Chapuis <i>et al.</i> (2015)	4.9	0.012	60	PIT tag	63-94	3.2-25.4	Yes (graphs)	No	Yes (inferred from table)
Bouinanc River (France)	Chapuis (2012); Chapuis and Tucker (2012)	-	0.016	20	PIT tag	64.5-87.5	299-775	Yes (graphs)	Yes (table)	Yes (inferred from table)
Durance River (France)	Milán (2013a, 2013b)	-	0.0023	40	PIT tag	40	150	Yes (graphs)	Yes (inferred from graphs)	Yes (inferred from graphs)
Halfmoon Creek (USA)	Schneider <i>et al.</i> (2014)	5.6	0.01	55	PIT tag	93-98	10-144.8	No	Yes (table)	No
Rede River (UK)	Schneider <i>et al.</i> (2014)	-	0.006	52-109	PIT tag	43-92	-	Yes	Yes (table)	No
Erlenbach (Switzerland)	Schneider <i>et al.</i> (2014)	~2.0	0.15	64	PIT tag/Magnetic	24-91	7-161	Yes (graphs)	No	Yes (inferred from table)
Rio Cordon (Italy)	Schneider <i>et al.</i> (2014)	-	0.13	90	Magnetic	52-100	1-142	Yes (graphs)	No	Yes (inferred from table)
Pigüeta River (Spain)	Vázquez-Tarrio and Menéndez-Duarte (2014)	70.0	0.007	56	Painted/Magnetic	11-77	6-66	Yes (graphs)	Yes (table)	Yes (inferred from table)
Coto River (Spain)	Vázquez-Tarrio and Menéndez-Duarte (2014)	17.0	0.01	88	Painted/Magnetic	17-20	11-19	Yes (graphs)	Yes (table)	Yes (inferred from table)
Aisne River (Belgium)	Houbrechts <i>et al.</i> (2015)	23.8	0.0053	92	PIT tag	62-97	1-271	No	No	Yes (inferred from table)
Strimm Creek (Italy)	Dell'Agnese <i>et al.</i> (2015)	-	0.08-0.15	62.3-76.1	PIT tag	54.7-97.7	1-580	Yes (graphs)	Yes (inferred from graphs)	Yes (inferred from graphs)
Wilket Creek (Canada)	MacVicar <i>et al.</i> (2015)	-	0.012	58-115	PIT tag	81-89	3-55	Yes (graphs)	No	Yes (inferred from table)
East Creek (Canada)	Papangelakis and Hassan (2016)	2.0	0.018-0.02	49-55	Magnets	77-88	0.25-36	Yes (graphs)	Yes (graphs)	No

Q<sub>bf</sub>: bankfull discharge; D<sub>50</sub>: median size of surface sediment.

## 2.2. Overview of compiled data

In terms of tracer type, the compiled data consists of 51% of points from experiments using PIT tags, and 13% and 36%, respectively, from experiments using painted stones and clasts with inserted magnets. Time trends in the utilized technique show a progressive shift from painted clasts toward magnets and PIT tags: earlier experiments (1960s–1980s) used only painted stones; magnetically tagged stones were introduced in the 1990s. PIT tags became the predominant method in the past decade. Average tracer recoveries are 81% and 71%, respectively, for PIT tags and magnets. They are considerably lower for painted stones, 58%, highlighting the poorer performance of this method compared with magnets and PIT tags which allow the retrieval of buried tracers. Tracer recoveries are comparable for inserted magnets and PIT-tags, suggesting that both strategies provide similar results. However, magnets have two disadvantages when compared with PIT tags: (i) magnetically tagged clasts need to be dug out (i.e. physically recovered) in order to be identified, and this may disturb bed structure (Hassan *et al.*, 1984); and (ii) they have a problem of decaying labels (Vázquez-Tarrío, 2013; Hassan and Bradley, 2017).

With regard to channel morphology, the data correspond with 58% RP channels, 31% SP channels, 9% PB channels and 2% multithread (MT) channels. Average tracer recoveries are similar for RP (68%) and SP systems (73%). The slightly larger average recovery ratio for the SP group of data is probably explained by a larger percentage of experiments using PIT-tags in SP (53%) than in RP data sets (47%). In order to avoid methodological biases in our analyses linked to differences in performance based on tracer type, we decided to focus only on those experiments for which tracer recoveries exceeded 75%. In addition, we excluded a few study cases in which the maximum distance of travel was not adequately surveyed.

## 2.3. Exploratory analysis of compiled data set

The first part of the data analysis was aimed at determining how much of the variance in data on tracer mobility and displacement could be explained by hydraulic forcing. The magnitude of tracer transport was determined from the mean travel distances of each tracer population. The degree of tracer mobility was computed using the fraction of mobile tracers: the ratio between the number of tracers that moved and the total number of tracers recovered. We chose to use specific stream power to characterize the flow magnitude of each transport episode. Stream power has traditionally been used in tracer studies (for example, Hassan *et al.*, 1992; Lamarre and Roy, 2008b; Schneider *et al.*, 2014; Papangelakis and Hassan, 2016) probably because estimating reach-averaged flow depth is difficult in steep mountain streams owing to the strong influence of local roughness elements on the water surface (Eaton and Church, 2011; Schneider *et al.*, 2014), and the fact that discharge is more readily available (Rickenmann and Recking, 2011). It also avoids the need to compute flow resistance. Eaton and Church (2011) and Diplas *et al.* (2016) proposed a dimensionless version of unit stream power, obtaining stronger scaling relationships between bedload and flow magnitude than those obtained using the dimensional form. We decided to use the non-dimensional version of stream power defined by Eaton and Church (2011) in order to avoid scale differences between the different study cases:

$$\omega^* = \frac{\omega}{\rho \cdot (g \cdot R \cdot D)^{3/2}} \quad (1)$$

where  $\omega^*$  is the dimensionless stream power,  $\omega$  is peak unit stream power (Bagnold, 1966, 1980) computed based on reported peak discharge data,  $R$  the submerged specific weight of sediment and  $D$  a representative grain size for the bed surface for which we used the median bed surface size ( $D_{50}$ ).

To account for a likely dependence of tracer transport on channel morphology, we normalized tracer travel distance by what we called the ‘morphological length scale’ of the channel, i.e. an approximate measure of the spacing between macroforms. In RP channels, pool–pool or riffle–riffle spacing is typically 5 to 7 times, and on average 5.7 times the channel width (Montgomery and Buffington, 1997). As such, we normalized tracer travel distances by 5.7 times the channel width for RP derived data. In SP channels, spacing between two step–pool units depends on several variables including slope (Church and Zimmermann, 2007) and is therefore only partially scaled with channel width. We used the formula presented by Abrahams *et al.* (1995) (Equation (2)). Recking *et al.* (2012) found output from this formula to be in good agreement with measured step–pool dimensions of 42 studied reaches in the French Alps and Vosges Mountains. It links step–pool spacing to step–heights and channel slope:

$$L = 1.493 \cdot H^{1.011} \cdot S^{-0.682} \quad (2)$$

where  $L$  is step–pool spacing,  $H$  the step–height and  $S$  channel slope. We approached step–height through the  $D_{84}$  of bed surface sediment. In multithread channels the definition of a morphological length scale is not as straightforward as in single-thread systems. In these settings, particle travel distances may scale with average bar spacing (Hundey and Ashmore, 2009). Hundey and Ashmore (2009) and Kasprak *et al.* (2015) observed that a confluence or diffuence occurs approximately once every 5.2 channel widths in braided rivers, consistent with the average pool spacing (5–7 channel widths) in many single-thread RP channels. We therefore used this value of 5.2 times the channel width for the MT data. Finally, in plane-bed (PB) channels, tracer travel distances were normalized directly by channel width. This normalization of tracer transport distances by morphological length scale was aimed at determining whether dispersed tracers travel further than one morphological channel-unit. It also serves as a basis for exploring how morphological units control the transport of gravels and the potential differences in downstream particle transport between different channel styles.

After considering the impact of flow magnitude on tracer transport/mobility, we proceeded to analyse the influence of hydrological controls, mainly the time duration of competent flow and the amount of time passing between tracer seeding and tracer dispersion. For some of the compiled tracer experiments (34 of 78 selected data points), the original study provided information about the flow duration above the critical threshold of sediment motion, allowing us to assess whether flow duration was correlated with the percentage of mobile tracers. In some cases, information was also available about the time that elapsed between tracer seeding and the subsequent competent flow, or between two successive transport episodes (27 of the 78 selected points). We used this information to explore whether antecedent, sub-threshold flows had an influence on tracer travel distances and the percentages of moving tracers.

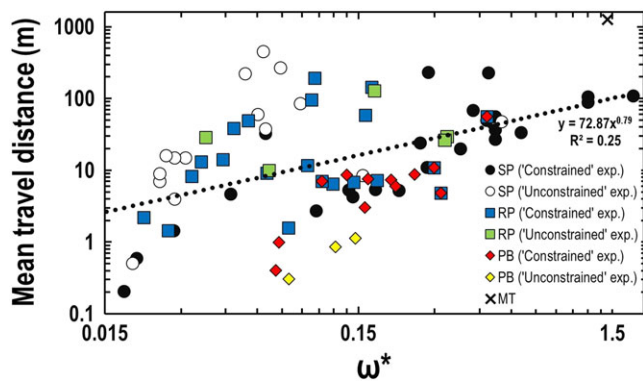
In all the analyses, we considered separately unconstrained and constrained-stone conditions. In the first kind of data, tracer stones are free compared with constrained conditions where they are arranged on the bed. Downstream tracer displacement was thus only dependent on absolute size effects

in the former, whereas in the latter downstream tracer travel depends on both size as well the ability of the flow to break up bed texture and particle arrangements. Re-entrainment of previously buried tracers may also play a role in constrained-stone data.

### 3. RESULTS

#### 3.1. Influence of flow magnitude on downstream tracer transport

We found a weak positive power correlation ( $R^2=0.25$ ,  $P$ -value=0.00<0.05) between tracer travel distance and non-dimensional stream power (Figure 1). In general,  $R^2$  increased when we split our data among the different channel styles (F1) and between constrained and unconstrained data (Table II). For equivalent hydraulic inputs, sediment is thus transported further during unconstrained experiments in SP channels (Figure 2(A)). In PB channels, sediment displacement is on average one order of magnitude lower than in SP and/or RP channels (Figure 1). In RP channels, data are segregated according to the width/bankfull depth ratio ( $W/d$ ), with larger tracer transport distances in wider channels ( $W/d>10$ ; Figure 2(B)); in narrow channels, distances of transport are one order of magnitude

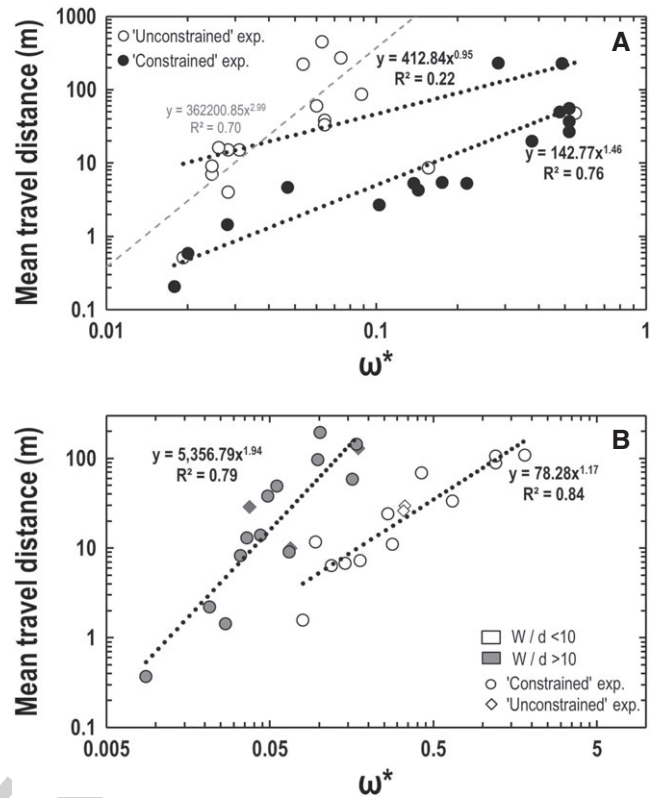


**Figure 1.** Mean travel distance of tracer population versus dimensionless peak stream power of the transport episode. Data were fitted to a power law. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

**Table II.** Summary of the correlations between tracer travel distance and dimensionless peak stream power. Correlations that were statistically significant (95% thrust level) are highlighted in bold characters

Data set	Mean travel distances			Mean scaled travel distances		
	$R^2$	$p$ -value	N	$R^2$	$p$ -value	N
All	0.25	0.00	78	0.30	0.00	78
SP: All	0.24	0.02	32	0.52	0.00	32
'Constrained'	0.76	0.00	16	0.83	0.00	16
'Unconstrained'	0.22	0.03	16	0.42	0.00	16
RP+MT: All	0.40	0.00	31	0.72	0.00	31
'Constrained'	0.44	0.00	26	0.72	0.00	26
'Unconstrained'	0.09	0.63	5	0.52	0.17	5
PB: All	0.68	0.00	15	0.66	0.00	15
'Constrained'	0.68	0.00	12	0.65	0.00	12
'Unconstrained'	0.99	0.06	3	0.99	0.06	3

N: number of data. SP: Step-pool. RP: Riffle and Pool. PB: Plane-bed. In this paper, power law fitting was always done in the same way: log-transforming the response and predictor variables, and doing an ordinary (linear) least squares fit.

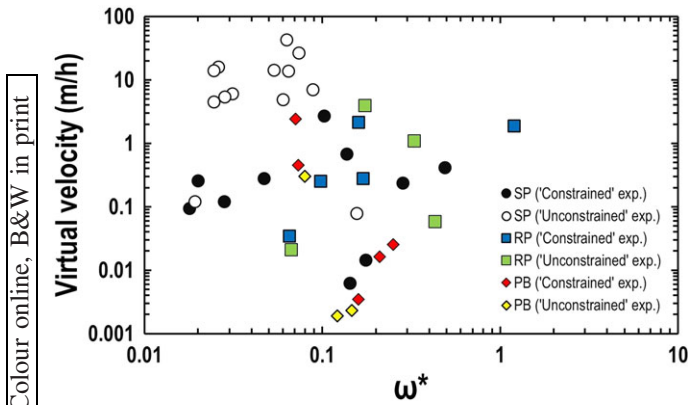


**Figure 2.** Mean travel distance of tracer population versus dimensionless peak stream power of the transport episode for: (A) step-pool data, and (B) riffle and pool data. Sources of data: SP (Dell'Agnese *et al.*, 2015; Dudley, 2007; Gintz *et al.*, 1996; Schmidt and Ergenzinger, 1992; Schneider *et al.*, 2014); RP (Bradley and Tucker, 2012; Haschenburger and Church, 1998; Houbrechts *et al.*, 2015; Papangelakis and Hassan, 2016). Dark lines in Figure 2(A) represent the best power-law fit found for each data set (constrained and unconstrained SP data), considering all data points in the regression; grey line represent the best power-law fit for unconstrained SP data, excluding two outliers.

lower and comparable with PB systems. Differences between narrow and wide channels are statistically significant at a 95% confidence level (ANCOVA test,  $P$ -value<0.05).

The  $R^2$  increases in the SP sub-data set when we consider separately constrained and unconstrained experiments (Figure 2(A)). These differences are once again statistically significant (ANCOVA test,  $P$ -value<0.05). However, there are no differences between the experimental conditions in the case of RP and PB channels (ANCOVA test,  $P$ -value>0.05). In addition, RP data tend to plot over SP data in constrained experiments (Figure 1), even though there is an important amount of overlap between both groups of data (particularly at large values of excess stream power). The different behaviour between both experimental conditions in SP and RP data suggest some influence of entrainment on tracer transport in the former that is lacking in RP channels: larger scale of macroroughness elements in SP channels may involve higher friction losses by form effects, and consequently a loss of entrainment efficiency for equivalent excess stream powers.

However, the observed differences between different channel styles and experimental conditions could be biased by differences in flood hydrographs (Comitti, in Hassan and Bradley, 2017). Shorter duration, flashy hydrographs may involve lower tracer transport than long, sustained floods. Unfortunately, information about flow duration was reported for relatively few of the data compiled. We estimated virtual velocities (tracer travel distance/flow duration) for these cases (Figure 3). However, the data are very scattered and do not show

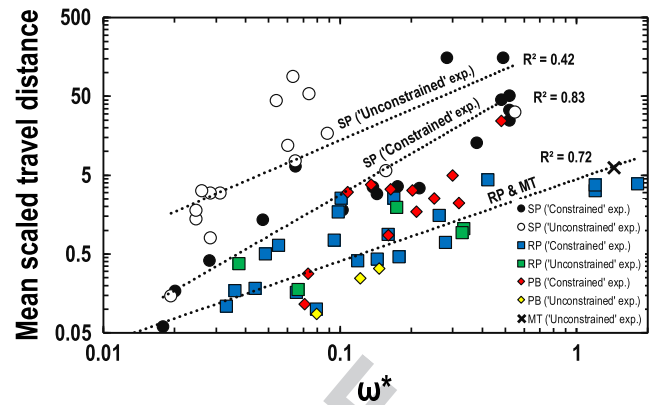


**Figure 3.** Virtual velocity of tracer dispersion plotted against dimensionless peak stream power. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

statistically significant correlations (Figure 3). Virtual velocities are probably more linked to time-integrated rather than to peak stream power (Haschenburger, 2013; Schneider *et al.*, 2014; Klösch and Habersack, 2018), and this may partially explain the strong scatter. There is also the problem of how to define the actual duration of competent flow. The information provided consisted normally in calendar time above a competence threshold defined for the entire bed (Gintz *et al.*, 1996; Ferguson and Wathen, 1998; Haschenburger and Church, 1998; Bradley and Tucker, 2012; Vázquez-Tarrió and Menéndez-Duarte, 2014; Dell’Agnese *et al.*, 2015), rather than using a grain-size based competence threshold as proposed by Milan (2013a) and Klösch and Habersack (2018). Nevertheless, the trends in Figure 3 are comparable with those seen previously for tracer distances. Differences between constrained and unconstrained conditions are only present in SP data. In addition, unconstrained SP data project over RP plots, suggesting that sediments travel farther and faster during unconstrained experiments in SP channels for equivalent hydraulic inputs. Furthermore, it seems that in RP channels there are no differences between transport episodes that are only dispersing surface sediment (equivalent to unconstrained conditions) and episodes that reorganize bed sediment texture (equivalent to constrained conditions). Conversely, in SP channels, significant, faster and further sediment displacement is possible without bed sediment disorganization, seen by comparing unconstrained and constrained experiments in Figure 2 and constrained and unconstrained experiments in Figure 3. Based on the weak correlation between virtual velocity and peak stream power shown in Figure 3, one could also argue that virtual velocity is roughly independent of stream power, particularly in SP constrained data (Figure 3). This may be related to the fact that strongest flows (in terms of peak stream power) last longer: this may partially counter the effects of increasing larger transport distances with increasing peaks of flow. This outlines the need to consider explicitly the influence of flow duration isolated from stream power in our analysis (see below in the text).

### 3.2. Influence of channel morphology on downstream tracer transport.

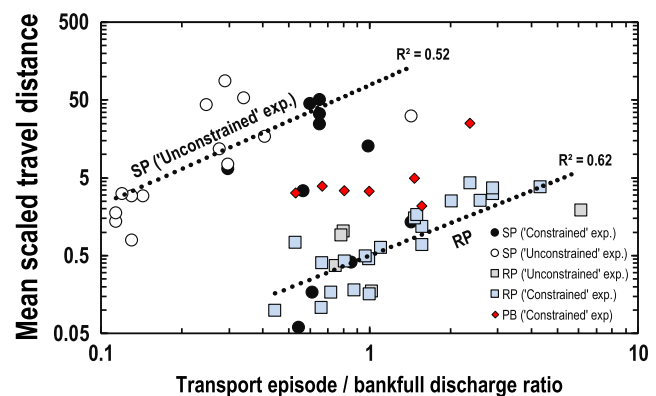
**F4** In Figure 4, tracer travel distances are divided by the estimated spacing between macroforms. In doing so, we see a stronger correlation between tracer travel distance and stream power (Table II). This suggests some dependence of tracer movement on channel morphology. However, the most important



**Figure 4.** Mean tracer travel distances normalized by the ‘morphological length’ of channel versus dimensionless peak stream power. Data were fitted to power laws. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

information provided by this plot concerns differences between SP and RP channels in the way tracers are conveyed downstream. According to Figure 4, tracer transport does not normally exceed by much one morphological unit (i.e. one riffle-pool sequence) in RP channels and it rarely reaches five morphological lengths, whereas in SP systems tracers can be easily exported out from one single step-pool unit. The differences between the channel morphologies are statistically significant (ANCOVA test,  $P$ -value < 0.05). We also evaluated the data in terms of flow recurrence, using the ratio of the discharge for the transporting episode to the bankfull discharge (Figure 5). **F5** Sediment does not travel further than one morphological unit during flows approaching bankfull in RP channels. In SP and PB channels, considerable tracer displacement is possible during flows below bankfull discharge, with clear differences between constrained and unconstrained cases in SP data: thus, gravels are transported downstream in SP systems more readily when the surface texture of the bed is disturbed (i.e. unconstrained vs constrained conditions, Figure 5).

The weak differences observed between constrained and unconstrained conditions in RP channels seems to contradict a large body of literature showing how tracers slow-down with time (Ferguson and Wathen, 1998; Ferguson *et al.*, 2002; Ferguson and Hoey, 2002; Haschenburger, 2011; Houbrechts *et al.*, 2011; Bradley and Tucker, 2012; Klösch and Habersack, 2018). For this reason, we decided to analyse with more detail the compiled data. We classified RP data according to ‘tracer



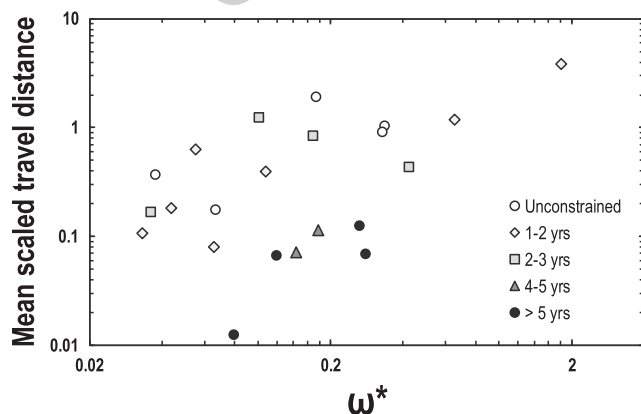
**Figure 5.** Mean tracer travel distances normalized by the ‘morphological length’ of channel plotted versus the ratio of discharge of the transport episode to bankfull discharge. Data were fitted to power laws. There are no unconstrained data for PB in this plot because there were no available data of bankfull discharge for this group of experiments. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

age': the number of years passing since tracers were seeded (Figure 6). We observed that 'older' tracer data (>5 years) tend to plot in the lower envelope of the point cloud in Figure 6, whereas 'younger' tracer data (<2 years plus unconstrained data) tend to plot in the upper envelope. Indeed, unconstrained data tend to overlap with tracers 'younger' than 3 years, but not with 'older' tracers. This observation may suggest that unconstrained and young constrained tracers have a comparable behaviour, while different behaviour appears between unconstrained and 'old' constrained data. All this indicates that the energy needed to displace tracers increase with 'tracer age' and is in good agreement with previous findings suggesting that tracer dispersion slows down with time (Ferguson and Wathen, 1998; Ferguson *et al.*, 2002; Ferguson and Hoey, 2002). This slowdown may be a consequence of particle trapping and burial (Hassan and Church, 1994; Haschenburger, 2011; Hassan and Bradley, 2017), and according to our results it seems to need some time before tracers become thoroughly mixed into the bed (>3–4 years).

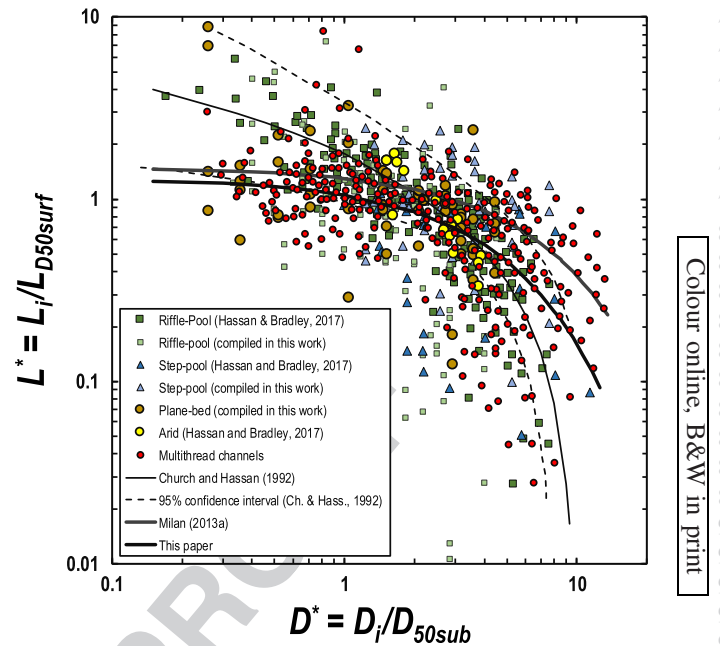
### 3.3. Influence of tracer size on downstream tracer transport

It has been near universally observed in tracer studies that smaller particles show larger displacements than larger particles (Church and Hassan, 1992; Hassan and Church, 1992; Ferguson and Wathen, 1998; Schneider *et al.*, 2014). After Church and Hassan (1992) and Hassan and Church (1992) it is well stated that grain size plays a role in downstream transport distance of particles coarser than the median grain size of the bed surface, with tracer travel distances decreasing strongly with particle size at these coarser terms of the grain size distribution.

**F7** In Figure 7 we have plotted mean tracer travel distance, scaled by the mean distance of travel of the median size class of surface sediment ( $L^*$ ), against the ratio between tracer size and the median size of the subsurface grain size distribution ( $D^*$ ). For this plot, we have used the large data set employed by Hassan and Bradley (2017) (after Church and Hassan, 1992), and we have incorporated new data compiled for the present research (Dudley, 2007; Liébault *et al.*, 2012; Milan, 2013b; Schneider *et al.*, 2014; Mao *et al.*, 2016; Papangelakis and Hassan, 2016). The new data add some scatter to the original data set of Hassan and Bradley (2017), but the plot continues to follow the general relation between tracer travel distance and tracer size proposed by Church and Hassan



**Figure 6.** Mean scaled travel distance plotted against the peak specific stream power. Data were grouped according to 'tracer age': time passing from tracer deployment to tracer survey.



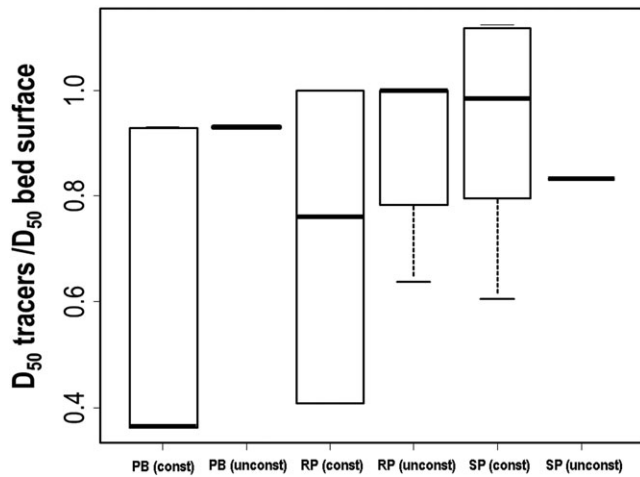
**Figure 7.** Scaled travel distance of individual particles as a function of scaled particle size. The travel distance of each size fraction ( $L_i$ ) is scaled by the travel distance of the size class that includes the median size of the bed-surface sediment ( $LD_{50surf}$ ). Tracer size is scaled ( $D_i$ ) by the median size of the subsurface grain size distribution ( $D_{50sub}$ ). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

(1992) and Hassan and Church (1992). The best regression fit that we have found for the data shown in Figure 7 is:

$$\log L^* = -0.26D^* + 0.26 \quad (n = 702, P < 0.001, R^2 = 0.272). \quad (3)$$

This regression equation follows a similar convex-up shape and only deviates to a small extent from Church and Hassan's (1992) curve: it plots slightly above for the coarser grain sizes, and slightly below for the finer ones. Furthermore, our curve is very close to that from Milan (2013a) for those grain sizes below the median size of the bed material. Both our curve and the fit found by Milan (2013a) fall in general between the 95%-confidence bonds of Church and Hassan (1992) and they show a similar size-selective behaviour: travel distance drops off rapidly for tracer grain sizes progressively coarser than the  $D_{50}$  of the bed material. In addition, the data from the different channel settings overlap strongly: this size-selective behaviour seems to be independent from the channel morphological style.

If tracer travel distances depend on tracer size relative to bed sediment, then some of the differences among PB, SP and RP data shown in the previous section could be biased by differences in tracer sizes. In order to address this issue, we looked at the relative size of tracers in relation to bed surface for the different groups of data (Figure 8) and we observed three things: **F8** (i) in general, many tracer studies use the surface  $D_{50}$  size-class as a reference for choosing the median size for the tracer population; (ii) in some RP and PB data, median tracer size is below surface  $D_{50}$ , which may contribute to larger displacements for the RP and PB data rather than the opposite trend observed in Figure 4; and (iii) tracer size relative to bed surface for constrained and unconstrained studies are comparable in the SP data set, so differences in tracer distances between the two conditions are not explained by differences in tracer size. These three observations lead to the same conclusions as the results shown in Figures 4 and 5 and confirm that tracer size was not

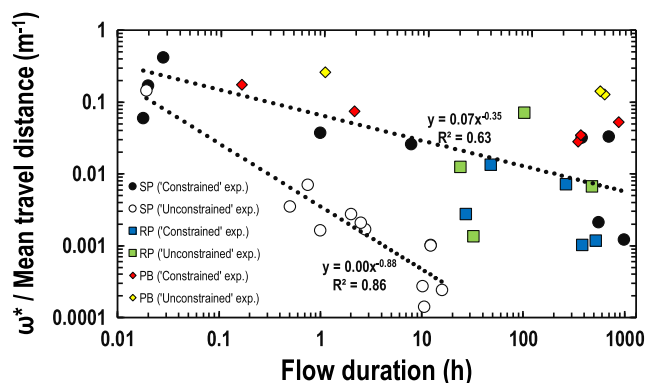


**Figure 8.** Median tracer size relative to bed surface D50 for the different groups of data.

a bias: gravels tend to travel across more morphological units in SP than in RP channels for similar hydraulic inputs, and this tendency is not dependent on the particle size.

### 3.4. Influence of flow duration and antecedent flow on tracer transport

While it seems obvious that a higher duration of competent flow would result in larger cumulated travel distances, differences may exist between channel style and/or experimental conditions. In order to deal with this issue, prior to analysing the effects of flow duration, we isolated the actual influence of duration of competent flow from the confounding effects of flow magnitude. We did this by estimating the ratio between stream power and tracer travel distance. This ratio is a proxy of the amount of energy expenditure needed to displace tracers one meter. Figure 9 shows this ratio plotted versus flow duration. The results suggest that the amount of energy required to displace tracers decreases with flow duration: increases in flow duration increment the time available to displace tracers a certain distance, and thus reduces the need for higher flow peaks. However, differences exist based on experimental conditions: for equivalent flow durations, tracer transport requires less energy expenditure under unconstrained conditions in SP channels. In addition, the slope of the plot is steeper suggesting a larger increase in tracer displacements with flow duration in unconstrained conditions.



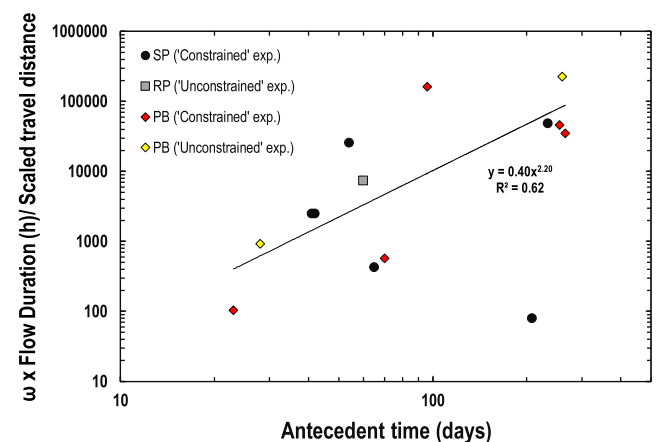
**Figure 9.** Ratio of dimensionless peak specific stream power to scaled travel distance plotted against flow duration. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

In order to assess the influence of antecedent sub-threshold flow on tracer transport, we analysed all available data on how much time had passed between tracer seeding and the subsequent competent flow and/or between the considered and the preceding transport episode. As in the case of flow duration, we isolated the actual influence of antecedent time from the confounding effects of flow magnitude by plotting the ratio between stream power and tracer travel distances (times the duration of competent flow) against antecedent time. The plot (Figure 10) shows how the length of antecedent time increases the amount of energy expenditure. This result suggests that interflow sub-threshold flows may play a role in enhancing particle arrangements and clast stability. This may include agitation and pivoting which contribute to stabilize clasts and moving free particles to protected positions in the channel.

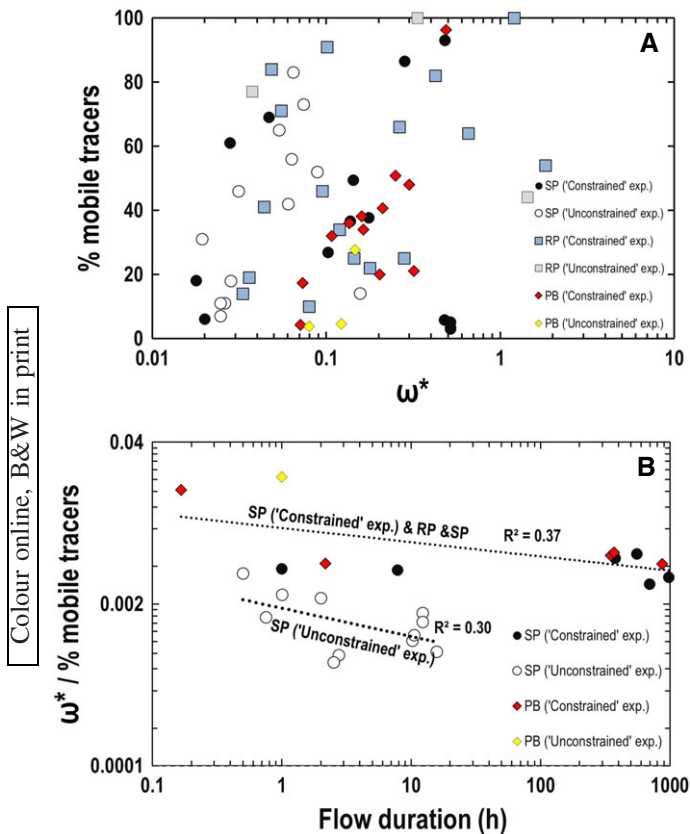
### 3.5. Tracer mobility

Despite the huge amount of scatter, the percentage of mobile tracers has a weak tendency to increase with stream power (at least for SP and PB data) (Figure 11(A)). PB- and constrained SP-data tend to plot in the right side of Figure 11(A), suggesting that bed disorganization requires larger hydraulic inputs in these channels. Lower stream powers are needed in the SP-unconstrained case to achieve similar percentages of tracer mobility as those observed in equivalent constrained experiments. RP data show a very large scatter and no clear link between stream power and percentages of mobile tracers.

The strong scatter of Figure 11(A) suggests that tracer mobility may be dependent on other hydrological constraints, for example flow duration. In Figure 11(B), the ratio between non-dimensional stream power and percentage of mobile tracers – a proxy of the amount of energy needed to displace a certain number of tracers – is plotted versus flow duration. This avoids the problem of comparing the influence of flow duration with data submitted to different flow conditions. Figure 11(B) shows that: (i) this ratio is higher for constrained compared with unconstrained conditions; and (ii) the ratio decreases more strongly with flow duration under unconstrained conditions in SP channels compared with constrained conditions (exponent of the power regression equation is double in constrained than in unconstrained SP data:  $-0.22$  vs  $-0.11$ ). In other words,



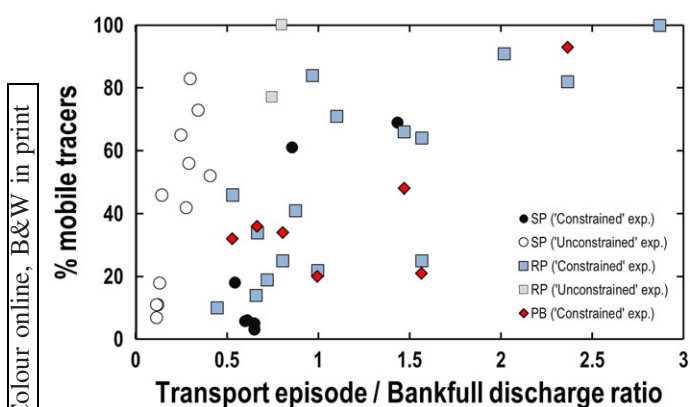
**Figure 10.** Ratio of dimensionless peak specific stream power (times flow duration) to scaled travel distance plotted against the time elapsed between tracer seeding and tracer movement or subsequent transport episodes. There are no unconstrained data for SP channels and constrained data for RP channels in this plot because there were no available data of antecedent time for these groups of experiments. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**Figure 11.** (A) Percentage of mobile tracers plotted against dimensionless peak stream power. (B) Ratio of dimensionless peak specific stream power to percentage of mobile tracers plotted against flow duration. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

when tracers are unconstrained, flow duration contributes to a certain amount of increase in percentages of mobile tracers because more time is available to displace the tracer population. Conversely, in constrained cases, the effect of an increase in flood duration is buffered by the need for some of this energy to be expended on disorganizing bed structures before tracers can be dispersed.

**F12** Figure 12 plots the percentages of mobile tracers versus the ratio of the discharge of the transport event to bankfull discharge. In RP channels there is a clear trend between flow magnitude and tracer mobility. In SP data there are differences between constrained and unconstrained conditions: 80–100% tracer mobility can be achieved by flow discharges lower than bankfull in SP unconstrained cases; for constrained conditions,



**Figure 12.** Percentage of mobilized tracers versus the transport episode/ bankfull discharge ratio. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

80–100% tracer mobility occurs at flow discharges around 2 times bankfull discharge while flows close to bankfull are characterized by less than 50% tracers in motion, and this is similar for SP and RP data. The results highlight the role of bed texture in constrained conditions and underscore two main points: (i) the degree of tracer perturbation in SP during floods depends not only on flow magnitude, but also on the degree of tracer stabilization by particle arrangements and bed texture; and (ii) the dominance of partial mobility over full mobility conditions in the available database of tracer experiments.

## 4. DISCUSSION

### 4.1. Influence of flow magnitude: potential sources of scatter in the data

Flow discharge is a major control on gravel transport. Stream power explained more than half of the variance in our data when adequately grouped according to a geomorphological criterion and experimental conditions (Table II). Comparable correlations between tracer travel distance and flow discharge have been found previously by, among others, Hassan *et al.* (1992), Schneider *et al.* (2014) and Houbrechts *et al.* (2015).

Concerning tracer mobility, we found a positive increase in the percentage of mobile tracers with flow magnitude; a comparable result was found by Phillips and Jerolmack (2014) or Papangelakis and Hassan (2016). Based on our analysis, high percentages of mobile tracers (exceeding 70%) in constrained experiments are only achieved during flows 1.5–2 times the bankfull (Figure 12), suggesting that partial mobility conditions dominate during more frequent floods, and that stable areas in the bed surface will persist from year to year. Similar results were found by Haschenburger and Wilcock (2003) in Carnation Creek: they found that only 20–50% of the bed surface was active for floods with a 2-year recurrence interval and that full mobility only occurred for floods with a 7-year recurrence interval.

The correlation between peak stream power and tracer transport found here, as well as in previous works (Hassan *et al.*, 1992; Schneider *et al.*, 2014), while statistically significant, shows strong scatter. This indicates that a large amount of variance in the data cannot be explained by flow discharge alone, prompting us to explore other potential controls. One such control was methodological uncertainties. For example, we used peak discharge in order to estimate stream power. However, stronger correlations may be found using stream power or discharge integrated over time (Haschenburger, 2013; Phillips *et al.*, 2013; Schneider *et al.*, 2014). Unfortunately, the compiled papers rarely provide this information and using peak discharge was the only possibility for performing a homogeneous analysis of all the compiled data. Furthermore, little information was provided in the original studies concerning the manner in which tracer distances were measured. Over the past decade, the use of highly accurate geolocalization devices (dGPS, Total Station...etc.) have become standard practice among geomorphologists and in tracer studies (Liébault *et al.*, 2012). However, in older tracer studies (Haschenburger, 1996; Haschenburger and Church, 1998), tracer travel distances were recorded using a tape measure running the length of the study reach. Another problem may be related to cross-sectional sediment dispersion. In this study, the focus was on transport of fluvial gravels in the downstream direction. However, a lateral or cross-sectional component for gravel displacement may exist (Dietrich and Smith, 1984; Seizilles *et al.*, 2014). As a result, sediment displacements may be

underestimated in some cases, particularly in morphological settings where there are no topographical constraints to bedload conveyance (e.g. plane-bed channels). Hardly any information about this cross-sectional particle shift could be found in the published studies. Yet another potential methodological constraint not considered here was the influence of the location of tracer seeding. In RP channels, Sear (1996) reported that travel distances were larger for tracers seeded on pool heads and tails compared with those seeded on riffles. Milan *et al.* (2002) and Milan (2013b) observed how tracers tend to follow streamlines and that those tracers seeded on riffles do not appear to be routed into pools. Likewise, Liébault *et al.* (2012) observed higher tracer mobility for tracers deployed in the low-flow channel than on gravel bars. We can therefore expect important differences in tracer dispersion depending on where the tracers were deployed, introducing an important source of scatter in data. Once again, this information is not typically provided in the original studies and is therefore difficult to assess. Potential sources of variance in the data related to hydrological and geomorphological controls will be explored in the following sections.

#### 4.2. Influence of channel morphology on gravel transport: general comments

It has long been recognized that channel morphology influences particle dispersion in gravel-bed rivers (Takayama, 1965; Laronne and Carson, 1976; Hassan *et al.*, 1991; Sear, 1996; Beechie, 2001; Pyrcce and Ashmore, 2003a, 2003b, 2005; Lamarre and Roy, 2008b; Milan, 2013b; Hassan and Bradley, 2017). In RP channels, pools and bars are a major control on gravel path lengths as suggested by Pyrcce and Ashmore (2003a, 2003b) who have shown that the mode of the path length distribution coincides with known pool–bar spacing. Bar spacing may also influence particle travel distances in braided rivers (Habersack, 2001; Hundey and Ashmore, 2009; Kasprak *et al.*, 2015). SP channels do not have bars, but it is to be expected that the movement of individual particles may be controlled by the large morphological features such as the steps and the pools (Lamarre and Roy, 2008b). Our results lead in the same direction: strength of correlation linking travel distance to stream power increases when tracer travel distances are normalized by the morphological length of channel.

Channel morphology does not only influence particle pathways, but the latter also contributes to the maintenance of bedforms (Sear, 1996; Milan *et al.*, 2002; Lamarre and Roy, 2008a; Milan, 2013b). Our results highlight some differences between SP and RP channels in the way moving gravels interact with macroforms. During more frequent floods, gravels in RP channels only tend to travel from one morphological unit to the next, while in SP streams tracers are conveyed more easily across several channel units. In addition, sediment travel distances in PB and narrow RP channels are considerably lower when compared with both wide RP and PB channels (Figure 2(B)). The observed differences among morphological styles described here may relate to cross-stream differences in channel topography (and bed shear stresses) and as such disparities in lateral dispersion and sediment trapping between the different settings.

#### 4.3. Gravel transport in plane-bed channels

Plane-bed morphologies in gravel-bed channels are featured by smooth beds and relatively simple trapezoidal cross-sections.

Friction losses due to form effects are then less important in PB channels compared with RP and SP, where hydraulics is complicated by a more heterogeneous cross-sectional morphology (Francalanci *et al.*, 2012). In this sense, PB streams have been considered similar to the flume (Recking *et al.*, 2016). In Figure 4 we showed that tracer travel distances for PB tend to plot in the lower envelope of the compiled data.

Bed structuration and particle arrangements may play a role in the lower tracer transport reported here for PB channels. In flat gravel-bed surfaces there have been described a set of surface structures as clusters, ‘stone cells’, stone lines or transverse ribs (Church *et al.*, 1998) that are frequent in natural gravel-, plane-bed rivers (Church and Zimmermann, 2007; Venditti *et al.*, 2017). These structures may be a major stability-promoting mechanism in plane-bed channels (Church *et al.*, 1998), increasing the needs for energy in order to displace tracers. Indeed, unconstrained PB data tend to plot over constrained PB data (Figure 4) highlighting the role of surface structuration on gravel transport in PB channels.

In addition, in PB channels there are no remarkable topographical constraints imposing a preferential gravel pathway. As such, sediments may be diffused not only downstream but they may also be diverted laterally (Seizilles *et al.*, 2014), decreasing the relative importance of the downstream component of tracer transport. Field observations by Papangelakis and Hassan (2016) in East Creek (Canada) suggested the same; after comparing tracer mobility maps for a RP- and a PB-reach (‘rapid’ morphology, in the sense of Zimmermann and Church, 2001), they observed how the mobility of tracers is more evenly spread across the bed in the PB reach, lacking preferential paths for tracer mobility.

#### 4.4. Gravel transport in step–pool channels

Step–pool channels are defined by channel-spanning ribs (steps) composed by an accumulation of jammed cobbles and boulders that are transverse or oblique to the channel (Zimmermann and Church, 2001; Chin and Wohl, 2005), alternating with pools containing finer bed material (Church and Zimmermann, 2007; Lamarre and Roy, 2008b). The SP morphology plays an important role in channel hydraulics, controlling hydraulic resistance (Wohl and Grodek, 1994; Abrahams *et al.*, 1995), energy dissipation (Hayward, 1980; Whittaker and Jaeggi, 1982) and defining a highly turbulent tumbling hydraulic regime (Peterson and Mohanty, 1960; Whittaker, 1987). Boulders are responsible for an important form of resistance as they give rise to leeside eddies (Wohl and Thompson, 2000; Church and Zimmermann, 2007), and at high flows energy is also dissipated by recirculating cells in the pools (Church and Zimmermann, 2007). These particular morphological and hydraulic features of step–pool channels should play a significant role in the distance of displacement of the bed material (Dudley, 2007; Lamarre and Roy, 2008b). Boulders and steps along the longitudinal profile of SP systems may act as a barrier to mobile particles (Sawada *et al.*, 1983). They may entrap particles and delay entrainment, and therefore influence travel distances. Pools may also act as sedimentation areas in SP channels (Schmidt and Ergenzinger, 1992). The average step–pool length may thus control the average travel distance of tagged clasts, as reported by Lamarre and Roy (2008b) in Spruce Creek. However, secondary modes in travel distance distributions of tracers have been documented in most SP channels, indicating that particles traverse several step–pool units during a flow event (Hassan and Bradley, 2017). Indeed, our analysis also confirms that tracers are able to traverse several step–pool pairs during high flows (Figure 4). Consequently,

steps are not totally 'impermeable' barriers. Topographic lows and highs could be identified in the cross-section of steps (Church and Zimmermann, 2007; Dudley, 2007), and the topographic lows may act as 'escaping' pathways for tracers during floods as observed by Dudley (2007). Furthermore, a combination of high turbulence and gravity may deflect gravel towards topographic lows during floods, allowing tracers to travel downstream further than a single step-pool unit (Dudley, 2007).

Travelling gravel interacting with the step-pool morphology may contribute to the bedform stability. The hydraulic (Whittaker and Jaeggi, 1982; Comiti *et al.*, 2005) or geomorphic (Church and Zimmermann, 2007; Curran, 2007) character of the processes leading to step formation and maintenance are still debated, but it is agreed that large boulders may act as anchor points to initiate step formation (Chin and Wohl, 2005; Church and Zimmermann, 2007; Lamarre and Roy, 2008a). According to Church and Zimmermann (2007), grains form interlocked chains across SP channels and thus interact to increase their threshold of motion ('jammed' state hypothesis). Lamarre and Roy (2008a) showed how the development and maintenance of sediment structures in a SP channel were mostly related to the entrapment and settlement of particles around kestones. This may explain while for frequent floods (Figure 5), tracer travel distances are around one to only a few step-pool units. Tagged particles may deposit mostly around kestones, becoming imbricated into sediment structures, increasing threshold stresses and remaining stored for several transport events (Lamarre and Roy, 2008a). However, large floods can cause the break up and rearranging of the SP structure (Church and Zimmermann, 2007; Zimmermann *et al.*, 2010). Field researchers have documented high bedload rates after large floods in SP channels (Gintz *et al.*, 1996; Lenzi *et al.*, 1999; Lenzi *et al.*, 2004; Turowski *et al.*, 2009) and this has been attributed to the decrease of form roughness of the channel bed and the fact that larger grains become more mobile after SP destabilization. This may explain our observation suggesting that tracers can travel farther than a few SP pairs during larger floods (Figures 4 and 5).

Moreover, mean tracer travel distances are considerably lower in constrained compared with unconstrained experiments in SP channels. Hence, SP channels appear to be steep enough to maintain significant transport of 'free' sediment, while lacking sufficient energy to disturb the coarser armoured bed sediment. This could have implications from the point of view of bedload supply: SP channels have sufficient capacities to transport allogenic sources of relatively fine sediment through the channel while the streambed remains stable (Piton and Recking, 2017). Field researchers have already shown that sediment transport rates in SP are dependent on sediment supply (Gintz *et al.*, 1996; Lenzi *et al.*, 1999; Lenzi *et al.*, 2004; Recking *et al.*, 2012; Kammerlander *et al.*, 2017). Indeed, the prediction of bedload transport in SP streams has been revealed to be very difficult due to its dependence on the availability of mobile sediment and related to the fact that many sediment transport equations do not account for the stress borne by immobile grains (Yager *et al.*, 2012a; Yager *et al.*, 2012b). In this sense, working in steep SP systems, previous authors have made a distinction between *travelling bedload* and *structured bedload* (Yu *et al.*, 2009). The *structured bedload* may define the scale of roughness elements in SP channels and influence flow resistance, while the *travelling bedload* may relate to the supply-limited and more mobile sediment introduced sporadically into the channel. Very recently, Piton *et al.* (2016) and Piton and Recking (2017) built on this concept of travelling bedload, which they explicitly state as an extension of the washing load concept to bedload transport. According to these

authors, in steep SP systems, relatively fine sediment supplied by external sources may be efficiently transported during floods, with marginal morphological activity and without the breaking up of coarse armoured surfaces (Egashira and Ashida, 1991; Piton and Recking, 2017). The different behaviour of constrained and unconstrained tracer experiments in SP data reported in this study leads to the same conclusion.

#### 4.5. Gravel transport in riffle and pool channels

Riffle-pool channels feature alternating areas of shallow (riffle) and deeper waters (pool) in a more or less regular pattern. Unlike SP and PB channels, bars are present in RP channels (Dietrich, 1987), and early studies already outlined the influence of bar morphology on gravel dispersion (Mosley, 1976; Kondolf and Mathews, 1986). Later, Pyrcce and Ashmore (2003a) reanalysed data from a wide range of river environments and found that distributions of travel distances in gravel-bed streams include modes corresponding to bars. Flume experiments by Pyrcce and Ashmore (2003b, 2005) also showed the role that bars have in tracer travel distances. Somehow, RP channels have a more developed cross-sectional morphology than PB and SP channels. This cross-sectional morphology results from the feedbacks that exist between the very specific patterns of flow conveyance and sediment routing in RP morphologies (Dietrich and Smith, 1983; Smith and McLean, 1984; Dietrich and Whiting, 1989), and the topography-driven sorting processes induced by bars (Dietrich and Smith, 1983; Dietrich and Smith, 1984; Paola, 1989; Nelson *et al.*, 2010). This results in high heterogeneity in elevation, roughness and surface grain size (Petit, 1987; Carling, 1991; Lisle *et al.*, 1991; Robert, 1997; Wilkinson *et al.*, 2008; Venditti *et al.*, 2012) that may involve great variability in shear stress distribution in RP channels (Whiting and Dietrich, 1991) and spatial contrasts in entrainment conditions between pools and riffles (Clifford, 1993; Sear, 1996). In a recent reanalysis of bedload measures in different bed morphologies, Recking *et al.* (2016) observed that larger corrections are needed in RP channels compared with SP and PB channels to compensate the bias introduced by averaging shear stresses when computing bedload transport (Francalanci *et al.*, 2012).

All the variability in roughness, shear stresses and reach-scale topography in RP morphologies influences bedload by concentrating the flow and the sediment in preferential paths. Coarser sediments are preferentially transported onto bar heads due to inertia effects. This zone grows and leads to secondary flows diverting the flow and finer sediments to the opposite side (see Figure 15 in Recking *et al.*, 2016), an effect that is also increased by differences in roughness (Lisle *et al.*, 1991; Nelson *et al.*, 2010; Recking *et al.*, 2016). Hence, variability in bed mobility across the RP sequence (Clifford, 1993; Sear, 1996; Hodge *et al.*, 2013) is responsible for intrinsic differences in sediment transport between riffle and pool, and shear stress gradients across and along RP channels determine scour in pools and deposition in riffles (Wilkinson *et al.*, 2004). Early painted stone experiments by Ashworth (1987) in Allt Dubhaig showed that tracers seeded in riffles had lower entrainment probability and lower mean travel distance than those seeded in pools. Conversely, Haschenburger and Church (1998) did not observe differences in tracer deposition according to tracer source. Haschenburger and Church (1998) also observed significant tracer deposition in pool areas. However, detailed observations made later by Milan *et al.* (2002) and Milan (2013b) showed how gravels tend to be routed out from pools and how the dominant depositional zones of tracer clasts in RP channels are the bars followed by the riffles (Milan, 2013b). Milan

(2013b) explained tracers occasionally found on pools as particles having been routed across bar surfaces and then rolled down the avalanche face into the pool (as in Dietrich and Smith, 1984).

Size selective deposition and particle paths have been described for RP channels. Sear (1996) observed how coarse gravels are normally stored in riffles and pool-heads while fine gravels are mainly stocked in mid-pool and pool-tails. He also reported that fine sediment travels across a riffle–pool–riffle sequence and concentrates in the downstream riffle. In addition, Milan *et al.* (2002) and Milan (2013b) observed grain size differences with flow magnitude. At low flows, fine sediment is routed onto riffles and pool-heads. Transport of gravel starts at moderate flows, being routed downstream from bar heads through bar-edges. At high flows, both fine and coarse sediment are transported onto the bar surface, depositing there in the falling limb of flow hydrograph. In those RP streams with high supply of fines, fine sediment deposited on riffles during high flows may be selectively winnowed onto the pools during the falling limbs of flow hydrographs (Lisle and Hilton, 1992).

In summary, the flow trajectories resulting from the RP cross-sectional variability influence the patterns of particle displacement and gravel routing in RP sequences. Gravel paths tend to follow streamlines contributing to maintain the RP morphology (Milan, 2013b). An important number of particles may be conveyed towards bar-heads and bar-tops during floods in RP channels (Milan, 2013b), i.e. stable positions reducing their potential for downstream transport. Bars seem to be a preferential storage site in RP channels, followed by riffles (Milan *et al.*, 2002; Milan, 2013b). Furthermore, Wathen (1995) and Bradley and Tucker (2012) reported that in RP channels a large number of tracers remained trapped in bars, even after several competent flow events. The result is a high efficiency of RP morphology for trapping sediment compared with SP or PB channels, as Figure 4 showed: (i) for similar hydraulic inputs, tracers travel across more morphological units in SP than in RP, on average; and (ii) mean travel distances, normalized by the morphological length of channel, scaled with stream power in RP channels with a gentler slope than they do in SP and PB channels (Figure 4). Bar morphology in RP channels is a very persistent feature, and it may continue to influence bedload paths and trapping gravels even during high flows (Milan, 2013b). This may explain the gentle scaling of travel distance with stream power in RP channels compared with SP, where step–pool destabilization during large floods may allow larger tracer dispersal.

#### 4.6. Gravel transport in multithread channels.

Even though we have reached a good scientific understanding of the mechanisms driving braiding morphodynamics (Ashmore, 1991, 2013), there is still a real gap in the availability of actual field data linking particle travel lengths and channel morphology in braided streams (Church, 2006; Kasprak *et al.*, 2015). There are no many systematic observations of tracer displacement coming from multithread and/or braided rivers (Kasprak *et al.*, 2015). Among the wide data set compiled for this work, only the upper reaches of the Alt-Dubhaig (Ashworth, 1987; Ferguson and Wathen, 1998), the Durance (Chapuis, 2012) and Bouinenc rivers (Liébault *et al.*, 2012) correspond to wandering/braided rivers. And unfortunately, the recovery ratios for two of these sites (upper reaches of the Alt-Dubhaig River and the Durance River) are not high (<75%). Due to this relative scarcity of systematic tracer studies in multithread or braided environments, understanding the grain-scale bedload transport processes and their relationship

to channel morphology in the field remains insufficient in braiding settings (Bertoldi *et al.*, 2014; Kasprak *et al.*, 2015; Recking *et al.*, 2016).

Early field and flume studies by Ashworth *et al.* (1992a, 1992b) and Ashworth (1996) on bar formation in braided rivers showed how flow divergences at emergent bar heads lead to the concentration of relatively coarse material and the routing of fine sediments into distributary channels. More recently, Hundey and Ashmore (2009) has hypothesized that bar spacing quantified by the distance between confluence/diffuence couplets may provide a first-order approach to gravel travel distances in braided channels. Habersack (2001) used particle radio tracking in the Waimakiri braided river (New Zealand) and provided early evidence for this, documenting the preferential deposition of tracked particles on an aggrading bar. More recently, Kasprak *et al.* (2015) used high-resolution elevation models derived from SfM photogrammetry in the flume in order to study the downstream transport of tagged particles in braided channels. They reported average sediment path lengths corresponding roughly with the average bar spacing. This study confirmed the influence of bars in acting as preferential depositional sites for tagged particles in braided rivers, with almost all retrieved tracers found in association with compound, lateral, diagonal and point bars. They documented that about 70% of tracers were found in bar-heads and margins, a smaller amount in bar-tops and only 3% in bar-tails. These observations agreed well with Ashworth's model of bar formation in braided rivers (Ashworth *et al.*, 1992b; Ashworth, 1996) that involves coarse sediment deposition around bar-heads and conveyance of more mobile sediment mainly through bar margins and distributary channels. Liébault *et al.* (2012) also found that bars were major storing zones in the wandering/braided Bouinenc River. These patterns of particle paths may promote a positive feedback reinforcing the location and persistence of gravel bars (Ashworth, 1996; Hundey and Ashmore, 2009; Kasprak *et al.*, 2015).

Kasprak *et al.* (2015) did not find any influence of seed location in the downstream deposition sites of tracers. However, Liébault *et al.* (2012) documented a clear influence of tracer source in particle travel distances in the wandering/braided Bouinenc River: they observed a 15–30-fold increase of dispersion for tracers initially seeded in the low-flow channel compared with those initially located in gravel bars. Based on their observations, they suggested that tracers initially seeded in the thalweg were not trapped by gravel bars and travelled far along the main channel. Methodological biases could explain differences between the flume results of Kasprak *et al.* (2015) and the field observations of Liébault *et al.* (2012): buried tracers were not recovered in the flume study of Kasprak *et al.* (2015). In this sense, Liébault *et al.* (2012) have shown that tracer travel distances of buried tracers are significantly larger – that is, the probability of tracer to be buried increases with its travel distance. According to this, frontrunners may not be adequately grasped in Kasprak's study. In addition, tracer recovery ratios were in general lower in Kasprak *et al.* (2015) than in Liébault *et al.* (2012).

#### 4.7. Influences of grain size

Results from tracer studies helped establish that the mean travel distance of fluvial gravels during competent floods is weakly correlated with the increasing particle size (Church and Hassan, 1992; Hassan and Church, 1992; Ferguson and Wathen, 1998; Schneider *et al.*, 2014). Church and Hassan (1992) and Hassan and Church (1992) related the mean travel distance of fluvial gravels to the particle size relative to the

median size of the bed material: particle size plays an important role in the downstream transport distance of tracers only at the coarser members of the bed grain size distribution ( $>2D_{50}$ ), whereas for intermediate grain sizes transport distances are mostly independent of clast diameter. Wilcock (1997) confirmed this relation in a flume, and several authors found similar trends with field data (Haschenburger, 1996; Ferguson and Wathen, 1998; Ferguson *et al.*, 2002; Vázquez-Tarrío and Menéndez-Duarte, 2014). Based on our data set compilation, in Figure 7 we have added new points to the plot originally presented by Church and Hassan (1992), Hassan and Church (1992) and Hassan and Bradley (2017): the new data introduce some amount of scatter, but in general the relation continues to hold. In addition, the relation seems to be pretty independent of the morphological style of channel.

In summary, particle size relative to bed sediment influences gravel transport distances that decrease with increasing clast size. According to Phillips and Jerolmack (2014) this decrease in travel distances with grain size is mostly controlled by competent flow duration. They observed how modal displacement lengths for particles of all sizes in a gravel-bed river were very similar at the individual flood scale. Conversely, Phillips and Jerolmack (2014) observed that cumulative travel distances showed a stronger inverse relation to grain size when measured over many transport events. Then, the relatively larger displacements for smaller particles shown in Figure 7 may result from a greater frequency of entrainment events during a flood for smaller particles compared with the coarser ones (Phillips and Jerolmack, 2014).

#### 4.8. Influences of the duration of competent flow and bed state

Our results show some increase in the degree of tracer mobility with a rise in the duration of competent flow: both tracer travel distance and percentage of mobile tracers tended to increase with flow duration (Figures 9 and 11(B)). Differences in behaviour exist here again, particularly between unconstrained and constrained conditions in SP channels. In unconstrained conditions, tracers are free to move, so their mobility increased more quickly with the increment in available time. Conversely, in constrained tests, it is the breakup of stable positions of tracers in bed structures and particle arrangement that predominantly determine tracer mobility, a process that is less dependent on flow duration.

A comparison of constrained and unconstrained data brings to light the influence of another control on particle travel distances that is not linked with either flow magnitude or channel morphology: the relationship between bed state and particle entrainment. A more stable coarse bed will act to reduce sediment mobility (constrained case) and increase energy expenditure required to move surface particles, an idea supported by results from Brayshaw *et al.* (1983), Hassan *et al.* (1992) and Hassan and Bradley (2017). Hassan and Bradley (2017) compared tracer data for gravel-bed streams with tracer data of gravel movement over a sand bed and they found travel distances in the second case to be typically one order of magnitude larger. In the same vein, Klingeman and Emmett (1982) reported that critical shear stresses for incipient motion were greater in the rising limb of a flood due to enhanced bed stability linked to initial armour. Similarly, Turowski *et al.* (2011) observed in four alpine streams that the discharge at the end of transport in the most recent event is correlated with the threshold discharge for the next event, which they interpret to reflect temporal changes in bed structure. In addition, Powell and

Ashworth (1995) observed how zones of contrasting bed structure may determine important differences on the entrainment thresholds.

#### 4.9. Influence of antecedent time and previous bed history

The inter-flood period has been historically ignored by fluvial geomorphologists as it is typically considered that the stability of the streambed could only be altered by above-threshold flows (Ockelford and Haynes, 2013). However, several studies have investigated the history of recent flows in the development of bed texture and the potential for influencing sediment dispersion. Olmeadow and Church (2006) reported on a field experiment aimed at studying the development of bed structure in a small headwater stream. In East Creek (British Columbia, Canada) they destroyed bed structures in one reach of the channel while leaving them intact in an adjacent one. Sediment yield from the disturbed reach was initially higher than from the undisturbed one. However, after several events, the mobility of larger clasts was substantially reduced, and they recorded direct evidence of structure development in the disturbed reach indicated by the movement and emplacement of marked grains. A similar experiment was carried out later by Lamarre and Roy using PIT-tags (Lamarre and Roy, 2008a). In addition, some of the papers compiled as part of this study report beautiful examples of how preceding flood history influenced tracer dispersion. One such case was reported by Gintz *et al.* (1996) for a study using magnetic tracers in the Lainbach river, a step-pool system in Germany. The morphological impacts of a large event resulted in a 10-fold increase in tracer travel distances in the subsequent extreme flood. In the Rio Cordon, Lenzi (2004) described a step-pool channel that was strongly modified after a large flood in 1994. Afterwards, sediment transport declined over several years as the channel re-established a relatively stable bed (Church and Zimmermann, 2007). Earlier studies also suggested that sub-threshold flows preceding threshold flows may influence gravel mobility. Laronne and Carson (1976) described the influence of bed sediment structures and arrangements on tracer dispersion. Reid and Frostick (1984) and Reid *et al.* (1985) found that threshold stresses were three times higher after a greater period of time before a flood in Turkey Brook (England), and they suggested that this could be related to the effects of bed re-structuration and particle interlocking during the inter-flood period. More recently, flume experiments have shown that not only threshold floods, but also prolonged inter-flood periods of sub-threshold flow promote bed stabilization (Monteith and Pender, 2005; Paphitis and Collins, 2005; Haynes and Pender, 2007). Ockelford and Haynes (2013) proposed two potential mechanisms for this: (i) vertical settlement of fine particles into low relief pore spaces of the river bed (Frostick *et al.*, 1984; Reid *et al.*, 1985; Marion and Weirich, 2003; Haynes and Pender, 2007); and (ii) local re-orientation and restructuring of surface particles (Reid and Frostick, 1984; Haynes and Pender, 2007; Mao, 2012). Very recently, Mao *et al.* (2017) reported that antecedent flow enhanced particle entrainment of tagged stones in the Saldur River (plane-bed to step-pool morphology).

Tracers constitute an excellent method to evaluate the effects of previous bed history on gravel mobility, but information about the time elapsed between tracer seeding and subsequent competent flows is not typically provided in papers. When available, it is difficult to isolate the role of antecedent time from other variables that exert an important control on tracer

dispersion, such as duration or excess stream power. The available data set is not large enough to allow selection of data with similar flow duration/competence but differing elapsed times. Furthermore, the number of days passing between tracer seeding and displacement is not a perfect proxy of a river bed's 'stress history'. It would be more interesting to have access to the actual number of days for which flow exceeded some sub-threshold discharge, or the actual value of specific stream power during the time period preceding tracer movement. However, this information is rarely available. Nevertheless, in constrained experiments it seems that tracer mobility decreases with increase in antecedent time (Figure 10). This suggests that sub-threshold flows might enhance particle packing and imbrication. We believe that more research should be carried out in the near future aiming at exploring this question and benefitting from the advantages offered by particle-tracking methods.

#### 4.10. Practical implications

The results of this paper may potentially have interesting implications for future research based on tracer data. When reporting the results of tracer experiments, researchers are encouraged to take more care to report on information that has been typically neglected, e.g. cumulative flow, duration of competent flow, description of bed structures, elapsed time between tracer seeding and subsequent surveys. Improvements have been made during recent years, and much more information can be found in recent papers compared with older ones (see Table I), but we should remain vigilant. We strongly believe that tracers have great potential to bolster our understanding of sediment transport providing that complete and homogeneous information is made available from the studies.

In addition, our review of previously published tracer experiences highlights that a large amount of research has been accomplished in single-thread channels, but we are still lacking data collected from multithread or braided channels. Braided rivers are featured by a very dynamic channel planform and a frequent downstream mobilization of bedload through a complex network of anabranches diverging and converging around gravel bars. This combination of factors makes braided rivers an ideal site to explore in the field on the relations between particles paths and channel morphology. However, few tracer studies have been performed in the field on multithread rivers (Chapuis, 2012; Liébault *et al.*, 2012), probably owing to the effort and time needed for surveying after floods in such large rivers. However, new solutions for tracking gravels based on active RFID technology that seem very promising for large rivers are being developed (Cassel *et al.*, 2017). More data from braided settings may be expected in the near future.

Finally, the results of this study may have implications for the design of tracer experiments and subsequent data analysis. With regard to constrained vs unconstrained conditions, special care should be taken when comparing results from different experiments. As we have shown here, constrained and unconstrained experiments are not necessarily equivalent. If the goal is to study particle entrainment and bed state evolution, the focus should be on results under constrained conditions. However, if the goal is to study trajectories of coarse sediment within a given setting (for example tributary junctions or step to pool), then results from unconstrained cases should be used.

## 5. CONCLUSIONS

In this paper, we compiled and analysed published data on sediment transport in gravel-bed rivers obtained in studies

based on passive tracers. Our results highlight three major controls on downstream sediment transport in gravel-bed rivers: (i) hydrological/hydraulic controls linked to discharge magnitude, the duration of competent flows, and antecedent sub-threshold flows; (ii) morphological controls associated with the average spacing between sediment storing areas; and (iii) controls exerted by bed structures and particle arrangements on threshold stresses.

As expected, we found significant correlation between flow magnitude (quantified using the stream power concept) and tracer travel distance, but with a non-negligible amount of scatter. We attribute differences in the length-scale of particle travel distances based on channel style to morphological controls and sediment 'trapping'. Concerning the positive impact of flow duration on the percentage of mobilized tracers, we attribute this to an increase in the duration of bed perturbation. Finally, although the data in this study are insufficient to draw decisive conclusions, they suggest that antecedent sub-threshold flows influence bed state thereby conditioning particle dispersion.

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## REFERENCES

- Abrahams AD, Li G, Atkinson JF. 1995. Step-pool streams: adjustment to maximum flow resistance. *Water Resources Research* **31**(10): 2593–2602.
- Ashmore PE. 1991. How do gravel-bed rivers braid? *Canadian Journal of Earth Sciences* **28**(3): 326–341.
- Ashmore PE. 2013. Morphology and dynamics of braided rivers. In *Treatise on Geomorphology*, Shroder I (ed), Vol. **9**. Academic Press: Waltham; 289–312.
- Ashworth PJ. 1987. *Bedload transport and channel change in gravel-bed rivers*. PhD Thesis, University of Stirling; Scotland.
- Ashworth PJ. 1996. Mid-channel bar growth and its relationship to local flow strength and direction. *Earth Surface Processes and Landforms* **21**: 103–123.
- Ashworth PJ, Ferguson RI, Ashmore PE, Paola C, Powell DM, Prestegard KL. 1992a. Measurements in a braided river chute and lobe. 2. Sorting of bedload during entrainment, transport and deposition. *Water Resources Research* **28**: 1887–1896.
- Ashworth PJ, Ferguson RI, Powell DM. 1992b. Bedload transport and sorting in braided channels. In *Dynamics of Gravel-Bed Rivers*, Billi P, Hey RD, Thorne CR, Tacconi P (eds). Wiley: Chichester; 497–513.
- Bagnold RA. 1966. An approach to the sediment transport problem from general physics. *United States Geological Survey Professional Paper* 4221.
- Bagnold RA. 1980. An empirical correlation of bedload transport rates in flumes and natural rivers. *Royal Society of London Proceedings*, A372, 453–473.
- Beechie TJ. 2001. Empirical predictors of annual bed load travel distance, and implications for salmonid habitat restoration and protection. *Earth Surface Processes and Landforms* **26**(9): 1025–1034.
- Bertoldi W, Recking A, Surian N. 2014. Braiding rivers: state of the art and future challenges. *Eos, Transactions American Geophysical Union* **95**(42): 381.
- Bradley DN, Tucker GE. 2012. Measuring gravel transport and dispersion in a mountain river using passive radio tracers. *Earth Surface Processes and Landforms* **37**: 1034–1045.
- Brayshaw AC, Frostick LE, Reid I. 1983. The hydrodynamics of particle clusters and sediment entrainment in coarse alluvial channels. *Sedimentology* **30**: 137–143.
- Butler RP. 1977. Movement of cobbles in a gravel bed stream during a flood season. *Geological Society of America Bulletin* **88**: 1072–1074.

- Camenen B, Le Coz J, Pacquier P, Lagouy M. 2010. *An estimation of gravel mobility over an alpine river gravel bar (Arc en Maurienne, France) using PIT-tag tracers*. 5th International Conference on Fluvial Hydraulics (River Flow 2010): Braunschweig, Germany 8–10 September 2010.
- Carling PA. 1991. An appraisal of the velocity-reversal hypothesis for stable pool-riffle sequences in the River Severn, England. *Earth Surface Processes and Landforms* **16**: 19–31.
- Carré DM, Biron PM, Gaskin SJ. 2007. Flow dynamics and bedload sediment transport around paired deflectors for fish habitat enhancement: a field study in the Nicolet River. *Canadian Journal of Civil Engineering* **34**: 761–769.
- Cassel M, Dépret T, Piegay H. 2017. Assessment of a new solution for tracking pebbles in rivers based on active RFID. *Earth Surface Processes and Landforms*. <https://doi.org/10.1002/esp.4152>.
- Chapuis M. 2012. *Bed Mobility in Highly Modified Fluvial Systems: Keys for Understanding River Management (Durance River, South-Eastern France)*. PhD Dissertation (in French). Université Aix-Marseille 1: Aix-en-Provence, France.
- Chin A, Wohl E. 2005. Toward a theory for step pool in stream channels. *Progress in Physical Geography* **29**: 275–296.
- Church M. 2006. Bed material transport and the morphology of alluvial river channels. *Annual Review of Earth and Planetary Sciences* **34**: 325–354.
- Church M, Hassan MA. 1992. Size and distance of travel of unconstrained clasts on a streambed. *Water Resources Research* **28**: 299–303.
- Church M, Hassan MA, Wolcott JF. 1998. Stabilizing self-organized structures in gravel-bed stream channels: field and experimental observations. *Water Resources Research* **34**: 3169–3179.
- Church M, Zimmermann A. 2007. Form and stability of step-pool channels: research progress. *Water Resources Research* **43**: W03415.
- Clifford NJ. 1993. Differential bed sedimentology and the maintenance of riffle-pool sequences. *Catena* **20**(5): 447–468.
- Comiti F, Andreoli A, Lenzi MA. 2005. Morphological effects of local scouring in step-pool streams. *Earth Surface Processes and Landforms* **30**: 1567–1581.
- Curran JC. 2007. Step-pool formation models and associated step-spacing. *Earth Surface Processes and Landforms* **32**(11): 1611–1627.
- Dell'Agnese A, Brardinoni F, Toro M, Mao L, Engel M, Comiti F. 2015. Bedload transport in a formerly glaciated mountain catchment constrained by particle tracking. *Earth Surface Dynamics* **3**: 527–542.
- Dietrich WE. 1987. Mechanics of flow and sediment transport in river bends. In *River Channels: Environment and Process*, Richards K (ed). Basil Blackwell: Oxford; 179–227.
- Dietrich WE, Smith JD. 1983. Influence of the point bar on flow through curved channels. *Water Resources Research* **19**(5): 1173–1192.
- Dietrich WE, Smith JD. 1984. Bed load transport in a river meander. *Water Resources Research* **20**(10): 1355–1380.
- Dietrich WE, Whiting P. 1989. Boundary shear stress and sediment transport in river meanders of sand and gravel. In *Water Resources Monograph*, Meandering R, Ikeda H, Parker G (eds), Vol. **12**. American Geophysical Union: Washington DC; 1–50.
- Diplas P, Chatanantavet P, Almedej J. 2016. Streambed structure, stream power and bed load transport: a unified outlook for gravel-bed and bedrock streams. In *River Flow*, Contastinescu G, García M, Hanes D (eds). Taylor and Francis Group: London; 987–994.
- Dudley J. 2007. *Channel Form, Flow and Sediment Transport in a Step-Pool Stream*. Loughborough University: PhD Dissertation.
- Eaton B, Church M. 2011. A rational sediment transport scaling relation based on dimensionless stream power. *Earth Surface Processes and Landforms* **36**(7): 901–910.
- Egashira S, Ashida K. 1991. Flow resistance and sediment transportation in streams with step-pool bed morphology. In *Fluvial Hydraulics of Mountain Regions*, Armanini A, Di Silvio G (eds), Vol. **37**. Springer: New York; 45–58. Lecture Notes in Earth Science
- Q7** Ergenzinger P, Schmidt KH. 1995. ~~Single particle bed load transport: first results from new approaches. *Zeitschrift für Geomorphologie, Suppl. Bd 100*: 193–203.~~
- Ferguson R, Bloomer D, Hoey T, Werritty A. 2002. Mobility of river tracer pebbles over different timescales. *Water Resources Research* **38**: 1045.
- Ferguson R, Hoey T. 2002. Long-term slowdown of river tracer pebbles: generic models and implications for interpreting short-term tracer studies. *Water Resources Research* **38**: 1142.
- Ferguson R, Wathen S. 1998. Tracer-pebble movement along a concave river profile: virtual velocity in relation to grain size and shear stress. *Water Resources Research* **34**: 2031–2038.
- Francalanci S, Solari L, Toffolon M, Parker G. 2012. Do alternate bars affect sediment transport and flow resistance in gravel-bed rivers? *Earth Surface Processes and Landforms* **37**(8): 866–875.
- Gintz D, Hassan MA, Schmidt KH. 1996. Frequency and magnitude of bedload transport in a mountain river. *Earth Surface Processes and Landforms* **21**: 433–445.
- Habersack HM. 2001. Radio-tracking gravel particles in a large braided river in New Zealand: a field test of the stochastic theory of bed load transport proposed by Einstein. *Journal of Hydrological Processes* **15**(3): 377–391.
- Haschenburger JK. 1996. *Scour and Fill in a Gravel-Bed Channel: Observations and Stochastic Models*. PhD Thesis, University of Vancouver: Canada.
- Haschenburger JK. 1999. A probability model of scour and fill depths in gravel-bed channels. *Water Resources Research* **35**: 2857–2869.
- Haschenburger JK. 2011. The rate of fluvial gravel dispersion. *Geophysical Research Letters* **38**.
- Haschenburger JK. 2013. Tracing river gravels: insights into dispersion from a long-term field experiment. *Geomorphology* **200**: 121–131.
- Haschenburger JK, Church M. 1998. Bed material transport estimated from the virtual velocity of sediment. *Earth Surface Processes and Landforms* **23**: 791–808.
- Haschenburger JK, Wilcock PR. 2003. Partial transport in a natural gravel bed channel. *Water Resources Research* **39**.
- Hassan M, Bradley DN. 2017. Geomorphic controls on tracer particle dispersion in gravel bed rivers. In *Gravel-Bed Rivers, Processes and Disasters*, Tsutsumi D, Laronne JB (eds). Wiley-Blackwell: UK; 439–466.
- Hassan M, Schick A, Laronne J. 1984. The recovery of flood-dispersed coarse sediment particles. *Catena Supplement* **5**: 153–162.
- Hassan MA. 1990. Scour, fill, and burial depth of coarse material in gravel bed streams. *Earth Surface Processes and Landforms* **15**: 341–356.
- Hassan MA, Church M. 1992. The movement of individual grains on the streambed. In *Dynamics of Gravel Bed Rivers*, Bill P, Hey CR, Thorne CR, Tacconi P (eds). John Wiley & Sons: Chichester.
- Hassan MA, Church M. 1994. Vertical mixing of coarse particles in gravel bed rivers: a kinematic model. *Water Resources Research* **30**: 1173–1186.
- Hassan MA, Church M, Ashworth PJ. 1992. Virtual rate and mean distance of travel of individual clasts in gravel-bed channels. *Earth Surface Processes and Landforms* **17**: 617–627.
- Hassan MA, Church M, Schick AP. 1991. Distance of movement of coarse particles in gravel bed streams. *Water Resources Research* **27**: 503–511.
- Hassan MA, Ergenzinger P. 2003. Use of tracers in fluvial geomorphology. In *Tools in Fluvial Geomorphology*. John Wiley & Sons, Ltd.
- Hassan MA, Roy A. 2015. Use of tracers in fluvial geomorphology. In *Tools in Fluvial Geomorphology*, 2nd edn. John Wiley & Sons, Ltd.
- Haynes H, Pender G. 2007. Stress history effects on graded bed stability. *Journal of Hydraulic Engineering* **133**(4): 343–349.
- Hayward JA. 1980. Hydrology and stream sediment from Torlesse stream catchment, Special Publication 17, Tussock Grasslands and Mountain Lands Institution, Lincoln College, [Lincoln, NZ](http://www.lincoln.ac.nz). **Q8**
- Hodge RA, Sear DA, Leyland J. 2013. Spatial variations in surface sediment structure in riffle-pool sequences: a preliminary test of the differential sediment entrainment hypothesis (DSEH). *Earth Surface Processes and Landforms* **38**(5): 449–465.
- Houbrechts G, Levecq Y, Peeters A, Hallot E, Campenhout JV, Denis AC, Petit F. 2015. Evaluation of long-term bedload virtual velocity in gravel-bed rivers (Ardenne, Belgium). *Geomorphology* **251**(15): 6–19.
- Houbrechts G, Levecq Y, Vanderheyden V, Petit F. 2011. Long-term bedload mobility in gravel-bed rivers using iron slag as a tracer. *Geomorphology* **126**(1–2): 233–244.
- Hundey EJ, Ashmore PJ. 2009. Length scale of braided river morphology. *Water Resources Research* **45**.

- Kammerlander J, Gems B, Köbler D, Aufleger M. 2017. Effect of bed load supply on sediment transport in mountain streams. *International Journal of Sediment Research* **32**(2): 240–252.
- Kasprak A, Wheaton JM, Ahmore PE, Hensleigh JW, Peirce S. 2015. The relationship between particle travel distance and channel morphology: results from physical models of braided rivers. *Journal of Geophysical Research Earth Surface* **120**.
- Keller EA. 1970. Bed-load movement experiments: dry creek, California. *Journal of Sedimentary Petrology* **40**: 1339–1344.
- Klingeman PC, Emmett WW. 1982. Gravel bedload transport processes. In *Gravel Bed Rivers: Fluvial Processes, Engineering and Management*, Hey RD, Bathurst JC, Thorne CR (eds). Wiley: Chichester; 141–169.
- Klösch M, Habersack H. 2018. Deriving formulas for an unsteady virtual velocity of bedload tracers. *Earth Surface Processes and Landforms*.
- Kondolf GM, Mathews WVG. 1986. Transport of tracer gravels on a coastal California river. *Journal of Hydrology* **85**(3–4): 265–280.
- Lamarre H, MacVicar B, Roy A. 2005. Using passive integrated transponder (PIT) tags to investigate sediment transport in gravel-bed rivers. *Journal of Sedimentary Research* **75**: 736–741.
- Lamarre H, Roy AG. 2008a. A field experiment on the development of sedimentary structures in a gravel-bed river. *Earth Surface Processes and Landforms* **33**: 1064–1081.
- Lamarre H, Roy AG. 2008b. The role of morphology on the displacement of particles in a step–pool river system. *Geomorphology* **99**: 270–279.
- Laronne J, Carson M. 1976. Interrelationships between bed morphology and bed material transport for a small, gravel-bed channel. *Sedimentology* **23**: 67–85.
- Lenzi M, Mao L, Comiti F. 2004. Magnitude-frequency analysis of bed load data in an Alpine boulder bed stream. *Water Resources Research* **40**.
- Lenzi MA. 2004. Displacement and transport of marked pebbles, cobbles and boulders during floods in a steep mountain stream. *Hydrological Processes* **18**: 1899–1914.
- Lenzi MA, D'Agostino V, Billi P. 1999. Bedload transport in the instrumented catchment of the Rio Cordon. Part I: analysis of bedload records, conditions and threshold of bedload entrainment. *Catena* **36**: 171–190.
- Leopold LB, Emmett WW. 1981. Some observations on the movement of cobbles on a streambed. In *Proceedings of the International Symposium on the Measurement of Erosion and Sediment Transport*, Florence, Italy, 22–25 June 1981. Publication no. 133, v. 2, International Association of Hydrological Sciences; 49–60.
- Liébault F, Bellot H, Chapuis M, Klotz S, Deschâtres M. 2012. Bedload tracing in a high-sediment-load mountain stream. *Earth Surface Processes and Landforms* **37**: 385–399.
- Liébault F, Laronne JB. 2008. Factors affecting the evaluation of bedload transport in gravel-bed rivers using scour chains and painted tracers: the case of the Esconavette Torrent. *Geodinamica Acta* **21**: 23–34.
- Lisle TE, Hilton T. 1992. The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams. *Water Resources Bulletin* **28**(2): 371–383.
- Lisle TE, Ikeda H, Iseya F. 1991. Formation of a stationary alternate bars in a steep channel with mixed-size sediment: a flume experiment. *Earth Surface Processes and Landforms* **16**: 463–469.
- MacVicar B, Chapuis M, Buckrell E, Roy A. 2015. Assessing the performance of in-stream restoration projects using radio frequency identification (RFID) transponders. *Watermark* **7**: 5566–5591.
- MacVicar B, Roy A. 2011. Sediment mobility in a forced riffle-pool. *Geomorphology* **125**: 445–456.
- Mao L. 2012. The effect of hydrographs on bed load transport and bed sediment spatial arrangement. *Journal of Geophysical Research Earth Surface* **117**.
- Mao L, Dell'Agnese A, Surian N. 2017. Sediment motion and velocity in a glacier-fed stream. *Geomorphology* **291**: 69–79.
- Mao L, Picco L, Lenzi MA, Surian N. 2016. Bed material transport estimate in large gravel-bed rivers using the virtual velocity approach. *Earth Surface Processes and Landforms* **4**(2): 595–611.
- Marion DA, Weirich F. 2003. Equal-mobility bed load transport in a small, step–pool channel in the Ouachita Mountains. *Geomorphology* **55**: 139–154.
- McNamara JP, Borden C. 2004. Observations on the movement of coarse gravel using implanted motion-sensing radio transmitters. *Hydrological Processes* **18**: 1871–1884.
- Milan DJ. 2013a. Virtual velocity of tracers in a gravel-bed river using size-based 829 competence duration. *Geomorphology* **198**: 107–114.
- Milan DJ. 2013b. Sediment routing hypothesis for pool-riffle maintenance. *Earth Surface Processes and Landforms* **38**(14): 1623–1641.
- Milan DJ, Heritage GL, Large ARG. 2002. Tracer pebble entrainment and deposition loci: influence of flow character and implications for riffle-pool maintenance. In *Sediment Flux to Basins: Causes, Controls and Consequences*, Jones SJ, Frostick LE (eds), Vol. **191**. The Geological Society: London; 133–148. Geological Society of London Special Publications
- Monteith H, Pender G. 2005. Flume investigations into the influence of shear stress history on a graded sediment bed. *Water Resources Research* **41**: W12401.
- Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* **109**: 596–611.
- Mosley MP. 1976. An experimental study of channel confluences. *Journal of Geology* **84**: 535–562.
- Nelson PA, Dietrich WE, Venditti JG. 2010. Bed topography and the development of forced surface patches. *Journal of Geophysical Research Earth Surface*: 115.
- Nichols M. 2004. A radio frequency identification system for monitoring coarse sediment particle displacement. *Applied Engineering in Agriculture* **20**: 783–787.
- Ockelford A, Haynes H. 2013. The impact of stress history on bed structure. *Earth Surface Processes and Landforms* **38**(7): 717–727.
- Oldmeadow DF, Church M. 2006. A field experiment on streambed stabilization by gravel structures. *Geomorphology* **78**: 335–350.
- Olinde L, Johnson J. 2013. *Characterizing coarse bedload transport during floods with RFID and accelerometer tracers, in-stream RFID antennas and HEC-RAS modeling*. AGU Fall Meeting Abstracts.
- Paola C. 1989. Topographic sorting. *Eos, Transactions American Geophysical Union* **70**: 332.
- Papangelakis E, Hassan M. 2016. The role of channel morphology on the mobility and dispersion of bed sediment in a small gravel-bed stream. *Earth Surface Processes and Landforms*.
- Paphitis D, Collins MB. 2005. Sand grain threshold, in relation to bed Stress history: an experimental study. *Sedimentology* **52**: 827–838.
- Peterson DF, Mohanty PK. 1960. Flume studies of flow in steep, rough channels. *Journal of Hydraulic Division – American Society of Civil Engineering* **86**: 55–76.
- Petit F. 1987. The relationship between shear stress and the shaping of a pebble-loaded river La Rulles-Ardenne. *Catena* **14**: 453–468.
- Phillips CB, Jerolmack DJ. 2014. Dynamics and mechanics of bed-load tracer particles. *Earth Surface Dynamics* **2**: 513–530.
- Phillips CB, Martin RL, Jerolmack DJ. 2013. Impulse framework for unsteady flows reveals superdiffusive bed load transport. *Geophysical Research Letters* **40**: 1328–1333.
- Piton G, Recking A. 2017. The concept of travelling bedload and its consequences for bedload computation in mountain streams. *Earth Surface Processes and Landforms*.
- Piton G, Vázquez-Tarrío D, Recking A. 2016. Can bed-load help to validate hydrology studies in mountainous catchment? The case study of the Roize (Voreppe – FR). FloodRisk, Lyon, E3S Web of Conferences (Volume 7), 04020, 12.
- Powell DM, Ashworth PJ. 1995. Spatial pattern of flow competence and bed load transport in a divided gravel bed river. *Water Resources Research* **31**: 741–752.
- Pyrce RS, Ashmore PE. 2003a. The relation between particle path length distributions and channel morphology in gravel-bed streams: a synthesis. *Geomorphology* **56**: 167–187.
- Pyrce RS, Ashmore PE. 2003b. Particle path length distributions in meandering gravel-bed streams: results from physical models. *Earth Surface Processes and Landforms* **28**(9): 951–966.
- Pyrce RS, Ashmore PE. 2005. Bedload path length and point bar development in gravel-bed river models. *Sedimentology* **52**: 839–857.
- Recking A, Leduc P, Liébault F, Church M. 2012. A field investigation of the influence of sediment supply on step-pool morphology and stability. *Geomorphology* **139–140**: 53–66.

- Recking A, Piton G, Vázquez-Tarrío D, Parker G. 2016. Quantifying the morphological print of bedload transport. *Earth Surface Processes and Landforms* **41**(6): 809–822.
- Reid I, Frostick LE. 1984. Particle interaction and its effect on the thresholds of initial and final bedload motion in coarse alluvial channels. In *Sedimentology of Gravels and Conglomerates*. *Canadian Society of Petroleum Geologists Memoir* **10**: 61–68.
- Reid I, Frostick LE, Brayshaw AC. 1992. Microform roughness elements and the selective entrainment and entrapment of particles in gravel-bed rivers. In *Dynamics of Gravelbed Rivers*, Billi P, Hey RD, Thorne CR, Tacconi P (eds). Wiley: Chichester; 253–266.
- Reid I, Frostick LE, Layman JT. 1985. The incidence and nature of bedload transport during flows in coarse-grained alluvial channels. *Earth Surface Processes and Landforms* **10**: 33–44.
- Rickenmann D, Recking A. 2011. Evaluation of flow resistance in gravel-bed rivers through a large field data set. *Water Resources Research* **47**.
- Q11** Robert A. 1997. Characteristics of velocity profiles along riffle-pool sequences and estimates of bed shear stress. *Geomorphology* **19**: 89–98.
- Rollet AJ. 2007. Etude et gestion de la dynamique sédimentaire sur une section fluviale à l'aval d'un barrage: le cas de la basse vallée de l'Ain. *Thèse de doctorat de géographie, université Lyon* **3**.
- Rollet AJ, MacVicar B, Piégay H, Roy AG. 2008. A comparative study on the use of passive integrated transponders to estimate sediment transport: first results (in French). *La Houille Blanche* **4**: 110–116.
- Sawada T, Ashida K, Takahashi T. 1983. Relationship between channel pattern and sediment transport in a steep gravel bed river. *Zeitschrift für Geomorphologie Suppl* **16**: 55–66.
- Schmidt KH, Ergenzinger P. 1992. Bedload entrainment, travel lengths, step lengths, rest periods – studied with passive (iron, magnetic) and active (radio) tracer techniques. *Earth Surface Processes and Landforms* **17**: 147–165.
- Schneider J, Hegglin R, Meier S, Turowski J, Nitsche M, Rickenmann D. 2010. Studying sediment transport in mountain rivers by mobile and stationary RFID antennas. In *Bundesanstalt für Wasserbau*. Braunschweig: Germany.
- Schneider J, Turowski J, Rickenmann D, Hegglin R, Arrigo S, Mao L, Kirchner J. 2014. Scaling relationships between bed load volumes, transport distances, and stream power in steep mountain channels. *Journal of Geophysical Research. Earth Surface* **119**(3): 533–549.
- Sear D. 1996. Sediment transport processes in pool–riffle sequences. *Earth Surface Processes and Landforms* **21**: 241–262.
- Sear D, Lee M, Oakley R, Carling P, Collins M. 2000. Coarse sediment tracing technology in littoral and fluvial environments: a review. In **Q12** *Tracers in Geomorphology*, Foster IDL (ed). Wiley.
- Seizilles G, Lajeunesse E, Devauchelle O, Bak M. 2014. Cross-stream diffusion in bedload transport. *Physics of Fluids* **26**.
- Q13** Smith JD, McLean SR. 1984. A model for flow in meandering streams. *Water Resources Research* **20**(9): 1301–1315.
- Takayama S. 1965. Bedload movement in torrential mountain streams. *Tokyo Geographical Paper* **9**: 169–188.
- Turowski J, Yager EM, Badoux A, Rickenmann D, Molnar P. 2009. The impact of exceptional events on erosion, bedload transport and channel stability in a step-pool channel. *Earth Surface Processes and Landforms* **34**(12): 1661–1673.
- Turowski JM, Badoux A, Rickenmann D. 2011. Start and end of bedload transport in gravel-bed streams. *Geophysical Research Letters* **38**(4).
- Vázquez-Tarrío D. 2013. *Transporte de sedimento como carga de fondo en la cuenca del río Narcea (vertiente Norte de la Cordillera Cantábrica)*. PhD Thesis. University of Oviedo: Oviedo (Spain).
- Vázquez-Tarrío D, Menéndez-Duarte R. 2014. Bedload transport rates for coarse-bed streams in an Atlantic region (Narcea River, NW Iberian Peninsula). *Geomorphology* **217**: 1–14.
- Vázquez-Tarrío D, Menéndez-Duarte R. 2015. Assessment of bedload equations using data obtained with tracers in two coarse-bed mountain streams (Narcea River basin, NW Spain). *Geomorphology* **238**: 78–93.
- Venditti J, Nelson PA, Bradley RW, Haught D, Gitto AB. 2017. Bedforms, structures mobile patches and sediment supply in gravel-bedded rivers. In *Gravel-Bed Rivers. Processes and Disasters*, Tsutsumi D, Laronne JB (eds). Wiley-Blackwell: UK; 439–466.
- Venditti JG, Nelson PA, Minear JT, Wooster J, Dietrich WE. 2012. Alternate bar response to sediment supply termination. *Journal of Geophysical Research* **117**.
- Wathen SJ. 1995, Scotland 289. *The effect of storage on sediment transfer processes in a small Scottish gravel bed river*. PhD Thesis. St. Andrews University.
- Whiting PJ, Dietrich WE. 1991. Convective accelerations and boundary shear stress over a channel bar. *Water Resources Research* **27**(5): 783–796.
- Whittaker JG. 1987. Sediment transport in step-pool streams. In *Sediment Transport in Gravel-Bed Rivers*, Thorne CR et al. (eds). John Wiley: Hoboken, NJ; 545–570.
- Whittaker JG, Jaeggi MNR. 1982. Origin of step-pool systems in mountain streams. *Journal of the Hydraulics Division – American Society of Civil Engineers* **108**: 758–773.
- Wilcock PR. 1997. Entrainment, displacement, and transport of tracer gravels. *Earth Surface Processes and Landforms* **22**: 1125–1138.
- Wilkinson SN, Keller RJ, Rutherford ID. 2004. Phase-shifts in shear stress as an explanation for the maintenance of pool-riffle sequences. *Earth Surface Processes and Landforms* **29**: 737–753.
- Wilkinson SN, Rutherford ID, Keller RJ. 2008. An experimental test of whether bar instability contributes to the formation, periodicity and maintenance of pool-riffle sequences. *Earth Surface Processes and Landforms* **33**: 1742–1756.
- Wohl EE, Grodek T. 1994. Channel bed-steps along Nahal Yael, Negev desert, Israel. *Geomorphology* **9**: 117–126.
- Wohl EE, Thompson DM. 2000. Velocity characteristics along a small step-pool channel. *Earth Surface Processes and Landforms* **25**: 353–367.
- Yager EM, Dietrich WE, Kirchner JW, McArdell BW. 2012a. Prediction of sediment transport in step-pool channels. *Water Resources Research* **48**(1).
- Yager EM, Turowski JM, Rickenmann D, McArdell BW. 2012b. Sediment supply, grain protrusion, and bedload transport in mountain streams. *Geophysical Research Letters*: 39.
- Yu GA, Wang ZY, Zhang K, Chang T, Liu H. 2009. Effect of incoming sediment on the transport rate of bed load in mountain streams. *International Journal of Sediment Research* **24**(3): 260–273.
- Zimmermann A, Church M. 2001. Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel. *Geomorphology* **40**: 311–327.
- Zimmermann A, Church M, Hassan MA. 2010. Step-pool stability: testing the jammed state hypothesis. *Journal of Geophysical Research. Earth Surface*: 115.