# **The effects of low-magnitude flow conditions on bedload mobility in a steep mountain stream**

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**ABSTRACT**

The transport of coarse material strongly controls the stability and evolution of mountain fluvial systems but, despite this, bedload dynamics are not yet fully understood especially in mountain streams. In this sense, particular attention was paid on the bedload magnitude (volume) expressed at event-scale and on the long-term, while few studies were focused on when and how the transport of the coarse material occurs. The aim of this work was to investigate the bedload mobility in the Rio Cordon, a mountain stream characterized by cascade and step-pool morphologies with a rough streambed. Here, the critical conditions for initiation of motion, transport distance and virtual velocity expressed by the coarse streambed material were assessed and their relationships with hydraulic forcing conditions and grain size were analyzed. To this end, a monitoring program based on bedload tracing was maintained over 7 years, allowing to analyze the bedload mobility during persistent high frequency/low magnitude flow conditions. To investigate the bedload mobility, 250 tracers were released between 2011-2012 and their propagation along study site was monitored until 2018. Overall, 14 tracer inventories were realized, determining 1697 tracer localizations. During the study period, the bedload dispersion resulted well described by the peak discharge magnitude (*Qp*,*qp* and *ωp* -*ωc*), while no significant relationships were observed with duration of competent flow (*tover*) and effective runoff volume (*ER*). Transport distance and tracer grain size were negatively correlated, whereas virtual velocity increased with increasing particle size. In this sense, the propagation velocity seems to be affected by the high frequency flows that, on the one hand triggered mobilization of the coarser tracers only through limited and impulsive events and, on the other hand favored a slowdown on the finer particles due to bedforms disturbance. Compared to other study sites, the Rio Cordon exhibited accentuated threshold conditions with lower transport distance and virtual velocity, confirming that steep mountain streams are generally influenced by a reduced transport efficiency due to protruding bedforms and macro-roughness that cause a pronounced energy dissipation. Interestingly, such condition seems to have progressively reduced from under- to near-bankfull flows. The results were compared to the bedload mobility observed in the Rio Cordon during 1993-1998, enabling to quantitatively assess how the bedload dispersion varied between a setting of stable armouring layer with protruding bedforms (2012-2018) and a partial alteration of these (1993-1998). An evident difference was observed in terms of transport distance, while critical conditions did not significantly change. Lastly, the long-term bedload tracing investigation highlighted that a certain legacy on the transport efficiency was produced by the persistent high frequency flow conditions. Over the study period, a general decrease of transport distance was observed that could be explained by a progressive stabilization of streambed material. Previous studies suggested that such condition can be interrupted by high magnitude/low frequency floods.

Keywords: sediment mobility, bedload tracing, critical conditions, transport distance, virtual velocity, Rio Cordon.

1. **INTRODUCTION**

Bedload transport is a crucial process that determine the morphology and dynamics of fluvial systems. The transport of coarse material controls the streambed stability and thus influences the presence and persistence of ecological niches (Habersack and Piégay, 2007), existence of spawning habitats for fish species (Junker et al., 2015; Wright and Minear, 2019), and channel morphology and evolution (Galia and Hradecký, 2014; Misset et al., 2020). This pivotal role in the hydromorphological processes was stressed even by the European Water Framework Directive, which recommended an accurate understood of bedload to achieve a good ecological status in the rivers. The impulsive transport of coarse material is also an important source of natural hazard, particularly, in mountain area (Badoux et al., 2014; Piton and Recking, 2017; Uchida et al., 2018), where the partitioning of sediment fluxes can exhibit large bedload fractions both over the short- and long-terms (Lenzi and Marchi, 2000; Turowski et al., 2010). However, our understanding of sediment dynamics in rivers remains rather limited and results particularly challenging in mountain streams. Indeed, in steep streams there is a complex interplay between sediment supply and occurrence of events able to transport sediments, increased by the presence of high gradients, highly heterogeneous grain size distributions, protruding bedforms and high variable hydraulic forcing conditions (Lenzi et al., 2004; Recking, 2012; Turowski et al., 2011; Masteller et al., 2019). In the near future, such knowledge gaps may be exacerbated due to the consequences of climate change and relative cascading processes that can alter sediment dynamics and sediment fluxes (Micheletti and Lane, 2016; Mazzorana et al., 2019; Comiti et al., 2019). In this sense, a valuable aid in understanding the bedload dynamics can be provided by the flume experiments, though upscaling the results from the laboratory to the field appears still challenging (Mao et al., 2016; Palucis et al., 2018; Plumb et al., 2020). In field experiments, several authors focused on the bedload magnitude, analyzing the volumes of coarse material transported in mountain streams at event scale or on the long-term (Rickenmann, 1997; D’Agostino and Lenzi, 1999; Turowski et al., 2009; Hiraoka et al., 2015; Rainato et al., 2017), while questions related to when and how sediment mobility occurs (e.g., threshold conditions, transport distance and propagation velocity) remain largely unanswered, with most of the investigation focused on single flood event or on the short-term (Lamarre and Roy, 2008; Dudley, 2007; Milan, 2013; Rainato et al., 2018a).

For the purposes of sediment transport monitoring over longer periods, the introduction of bedload tracing approach dates back to the 60’s with streambed particles being simply painted (Takayama, 1965; Leopold et al., 1966). Starting from these pioneering studies, the tracing technique improved over the years through the use of magnetic tags (Schmidt and Ergenzinger, 1992) up to the most recent passive or active transponders based on Radio Frequency Identification (RFID) technology (Nichols, 2004; Lamarre et al., 2005; Bradley and Tucker, 2012; Liébault et al., 2012; Cassel et al., 2017). In particular, the RFID technology enabled to identify each particle traced by a unique identification code and to precisely detect the tracer also in case of coverage by water, soil, rock or wood (Schneider et al., 2014; Parsons et al., 2018; Kayad et al., 2019). Generally, the field investigations based on bedload tracing resulted particular suitable for the narrow mountain streams, while in the wider channels there were evident limitations due to the low recovery rates and reduced safety conditions (Vázquez-Tarrío and Menéndez-Duarte, 2014). Starting from the studies done in the 60’s, the tracing of coarse streambed material allowed to gather evidence on threshold conditions for the initiation of motion (Church and Hassan, 2002; Houbrechts et al., 2015), sediment transport distance (Gintz et al., 1996; Dudley, 2007, Ivanov et al., 2020), bedload transport rates (Haschenburger and Church, 1998; Liébault et al., 2012), thickness of the active layer (Schneider et al., 2014), propagation velocity (Ferguson and Wathen, 1998; Milan et al., 2013) and bedload volume triggered by flood events (Liébault and Laronne, 2008). Also, bedload tracing techniques permitted to better comprehend the channel evolution in gravel bed rivers (Chapuis et al., 2015) and to investigate the sediment propagation from source areas to channel network (Oss Cazzador et al., 2020).

Many authors demonstrated that the hydraulic forcing conditions are crucial controlling factors for bedload mobility. Particularly, linear or power law relationships between bedload dispersion and peak of water discharge, shear stress, unit water discharge and excess stream power were observed (Church and Hassan, 2002; Lenzi et al., 2006a, Lamarre and Roy, 2008; Vázquez-Tarrío et al., 2019). Nevertheless, in complex fluvial systems as mountain streams the bedload mobility is not only controlled by flow conditions but even stream gradient, channel morphology, bedforms, streambed configuration and particle size can act as controlling factors (Bathurst, 2007; Vázquez-Tarrío and Batalla, 2019). The highly heterogeneous bed material lead to high roughness that, in conjunction with form-drag due to protruding bedforms (i.e., cascade, step-pool), limit the energy available for the particle motion (Lenzi et al., 2006a; Nitsche et al., 2011). Additionally, in the poorly sorted streambed material the coarser clasts are more exposed than the hidden fine particles and, thus, easier mobilized (Andrews, 1983; Mao and Lenzi, 2007). In mountain stream, persistent ordinary frequency flow conditions and low sediment supply can favor the development of an armouring layer, with larger bed material in the surface layer. This configuration strongly stabilizes the streambed by limiting erosion and transport of finer grain size fraction (Church and Hassan, 2002). The complex transport dynamics of mountain stream is stressed even by the influence of particle sizes on their mobility. In fact, Church and Hassan (1992) and Schneider et al. (2014) observed negative correlation between grain size and transport distance, while Milan (2013) noted an increase of bedload propagation velocity with coarsening particle size. However, some authors noticed equal mobility conditions during higher magnitude flows, with bedload mobility unaffected by the particle size (Marion and Weirich, 2003; Mao and Lenzi, 2007). In that regard, Dell’Agnese et al. (2015) documented a low dependency of displacement on particle size, with all tracers that, for a given flow condition, moved with comparable distances along the Strimm Creek. This finding is coherent with what observed in the Saldur River by Mao et al. (2017), who found that both the discharge associated to the initiation of motion and the virtual velocity weakly correlated with the particle size.

Based on a tracing investigation conducted in a mountain stream during 7 years, this work aims to analyze the bedload mobility during high frequency/low magnitude flow conditions. Particularly, the dataset collected allowed to (i) determine the critical conditions for motion of grain size classes traced; (ii) estimate the transport distance expressed by the tracers over the study period investigating its relationships with hydraulic forcing condition and particle size; (iii) calculate the virtual velocity shown by the tracers, permitting to comprehend the bedload propagation velocity in the study site, and explore its relationships with flow condition and particle size.

1. **MATERIAL AND METHODS**
   1. **Rio Cordon study site**

Rio Cordon (Fig. 1) is a mountain stream that drains a 5 km2 basin located in the Dolomites (eastern Italian Alps). The catchment ranges between 1763 and 2763 m a.s.l. and is geologically dominated by dolomite with a wide presence of limestone, volcanoclastic conglomerates, tuff sandstones and calcareous outcrops. Given the elevation, the basin area is poorly forested (7%) and largely covered by Alpine grassland (61%). The average annual precipitation is around 1150 mm, characterized by snowfalls between December-April, rainstorms in summer, and persistent showers in autumn. Consequently, the catchment exhibits a typical nivo-pluvial flood regime (Rainato et al., 2018b). The slopes of the watershed are quite steep (~ 27°), while the main channel features an average gradient of 17% and a mean bankfull width equal to 5.3 m (Mao and Lenzi, 2007). Following Montgomery and Buffington (1997), the main channel can be described as characterized by cascade and step-pool morphologies, with a rough streambed dominated by cobbles and boulders (Fig. 1). Surface sediments are poorly sorted, with *D16*, *D50*, and *D84* equal to 29, 114, and 358 mm, respectively, and a persisting armoured layer (Mao et al., 2010; Rainato et al., 2017). In the Rio Cordon, the bankfull discharge (*Qbf*) was estimated in 2.30 m3 s-1 (Lenzi et al., 2006b).

### Fig.1 ###

* 1. **Bedload tracing**

The bedload tracing method was used to investigate the sediment mobility in the Rio Cordon (Liébault et al., 2012). Particularly, 250 particles (hereinafter “tracers”) were sampled from the streambed material, colored, equipped with 23-mm passive RFID transponders, measured in size and seeded onto the channel bed along release sections located 320 m upstream the Rio Cordon monitoring station (Fig. 1b). This study reach nearly coincides with that monitored by Lenzi (2004), Lenzi et al. (2006a), Mao and Lenzi (2007), to investigate the sediment mobility along the Rio Cordon, also extending slightly upstream. In agreement with Gintz et al. (1996) who suggested tracing at least the range *D30*-*D70* to properly investigate the bedload mobility, the tracers installed in the Rio Cordon ranges between 33 and 210 mm, corresponding to *D20* < *D* < *D70* of the streambed surface material. In terms of grain size, the tracers can be grouped into 6 *b-axis* classes (hereinafter “tracer size classes”), from very coarse gravel to large cobbles following the Wentworth classification (Bunte and Abt, 2001). The tracers were seeded between May 2011 and May 2012, while their position was surveyed since November 2012 (first tracer inventory), thus enabling tracers to assume a natural arrangement along the streambed (Vázquez-Tarrío and Menéndez-Duarte, 2014; Houbrechts et al., 2015). From the release sections, the tracers were left to move downstream through cascade, step-pool and rapid configurations along a reach with mean slope equal to 0.125 m m-1. A laser rangefinder (accuracy = 0.01 m) in conjunction with a prism were used to survey the longitudinal profile, surveying 360 points along the streambed (1.12 points m-1). A mobile RFID loop antenna was used to detect the tracers’ position, while the displacements were measured by a laser rangefinder. Given the rough and steep nature of the channel and the large size of the antenna (0.53 m) only displacements longer than 1 m were considered as effectively mobilized. When found during the surveys, the mobilized tracers were never removed and relocated again at the release sections, but were instead left untouched, allowing them to move along the entire study reach and being progressively incorporated in the bed structure (Liébault et al., 2012; Houbrechts et al., 2015). A detailed description about the materials and methods used during the tracer inventories can be found in Rainato et al. (2018a). Overall, 14 tracer surveys were conducted during the study period (Fig. 2), with 1697 tracers being found in the channel bed, 528 of which featured a displacement above the minimum threshold of 1 m.

### Fig. 2 ###

* 1. **Characterization of hydraulic forcing conditions**

In this work, the hydraulic forcing conditions were estimated on the basis of the water discharge measured at the monitoring station. Since 1986, in the Rio Cordon basin there is a permanent monitoring station, which continuously records the climatic conditions as well as the water and sediment fluxes. A water level gauge on the inlet channel measures the water discharge (*Q*). Under ordinary conditions (*Q* ≤ 1.00 m3 s-1) the discharge is recorded hourly, while the time sampling increase to 5 min when *Q* > 1.00 m3 s-1. Currently, the monitoring station is managed by ARPA Veneto (Regional Department for Land Safety) that guarantees the maintenance and calibration of the installed instruments. Detailed descriptions about the monitoring facilities can be found in several previous papers (e.g., Lenzi et al., 1990; Rickenmann et al., 1998; Mao et al., 2010; Rainato et al., 2017; Pagano et al., 2019). For the purposes of this work, the hourly discharge measured at the monitoring station was used since it appears representative in describing the hydraulic forcing experienced by the tracers installed along the streambed. Indeed, no tributary is present between the tracers’ release sections and the monitoring station (Fig. 1a). Also, during the study period (i.e., May 2012-October 2018), only a time fraction equal to 21% of the discharge measurements presented gaps and these were mainly due to flows too low to be gathered by the water gauges (~ *Q* < 0.03 m3 s-1), condition that occurred mainly in winter and early spring (Fig. 2). Starting from the *Q* measured by the monitoring station, in each intra-survey periods (Fig. 2) a set of variables were therefore estimated to describe the hydraulic forcing conditions occurred. According to Hassan et al. (1992), Lenzi (2004), Lamarre and Roy (2008), Schneider et al. (2014) and Vázquez-Tarrío et al. (2019), the relationships between hydraulic forcing and bedload mobility were then tested through power law regressions. Specifically, the variables analyzed are the maximum (*Qp*), mean (*Qmean*), median (*Qmed*) water discharge and the peak of unit discharge (*qp*). The identification of the critical discharge for initiation of motion (*Qc*) enabled also to evaluate the excess stream power (Hassan and Church, 1992; Gintz et al., 1996), considered as the difference between the peak (*ωp*) and the critical stream power for tracers motion (*ωc*). The specific stream power (*ω*) was calculated using Eq. (1):

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| --- | --- | --- |
|  |  | (1) |

where *ρ* is the fluid density (kg m-3), *g* the gravitational acceleration (m s-2), *Q* the water discharge (m3 s-1), *s* is the local slope (m m-1) and *w* the flow width (m). In this work, *s* is 0.125 m m-1 and is based on the longitudinal profile of the study reach (see section 2.2). To define the flow width, a stable cross section was equipped with a capacitive piezometer, sampling every 15 min the water stage. The availability of the cross section’ topography (surveyed by laser rangefinder and prism) and the relative water stages, permitted to define *w*. The flow width thus obtained can be understood as a good proxy for the entire reach investigated, since the stable cross section was established along a stream segment with constant width. In addition to Eq. (1), *w* was even used to determine the unit discharge *qp*. The identification of *Qc* permitted also to estimate the over-threshold time (*tover*) and the effective runoff volume (*ER*) in each intra-survey period. In this sense, *ER* corresponds to the hydrograph volume exceeding the threshold for motion (Rickenmann et al., 2012; Rainato et al., 2017). The continuous measurement of *Q* enabled also to determine the dominant flow regime in each intra-survey period (Dell’Agnese et al., 2015). To this end, three classes were used to distinguish, respectively, intra-survey periods dominated by snowmelt-induced flows (S), rainfall-driven flows (R) or mixed-nature flows (M). The R class clusters regimes dominated by summer rainstorms or autumnal precipitations, while the M group express the prevalence of rain-on-snow flows.

* 1. **Estimation of sediment mobility**

The tracer inventories permitted to define, for each intra-survey period, the mobilized grain size classes, the transport distance exhibited by every tracer respect to the previous survey and, by defining the over-threshold flow duration of the corresponding tracer size class, its virtual velocity.

The critical discharges (*Qci*) for the motion of each *i* tracer size classes were defined following the flow competence method (Andrews, 1983; Mao et al., 2008; Dell’Agnese et al., 2015). Thus, based on the tracer inventories, *Qci* was determined as the minimum *Qp* for which the entrainment of the *i* class was observed. The analysis of the critical conditions was integrated even with the evidences about the flood competence. As demonstrated by Lenzi et al. (2006a) and Mao et al. (2008), the integration of flow and flood competence permits to better comprehend the bedload mobility, since the former describe the local mobility, in this work the tracer displacements, while the latter express conditions of active bedload transport, here, the largest clast gathered by the Rio Cordon monitoring station. In particular, the largest particle transported to the monitoring station by a single flood event was associated with the relative flood peak. During the study period, 5 flood events able to transport material up to the monitoring station were recorded (Table 1). In the Rio Cordon, this approach was formerly used by Lenzi et al. (2006a), who noted critical discharges that ranged between 0.50 m3 s-1, necessary for the entrainment of particles with diameter = 38 mm, to 10.41 m3 s-1 required to mobilize boulders with *b-axis* equal to 1024 mm.

### Table 1 ###

The inventories allowed to determine the displacement (*L*) exhibited by each tracer respect to the previous localization and, thus, the mean transport distance (*Lm*) expressed by the tracers in each intra-survey period. According to Gintz el al. (1996), Lenzi et al. (2006a), Mao et al. (2007), Liébault et al. (2012) and Houbrechts et al. (2015), *Lm* was calculated considering all tracers detected (including those that did not move). In addition to the hydraulic forcing conditions, the influence of the tracer size on bedload mobility was also investigated. For this purpose, Church and Hassan (1992), collecting data published about bedload tracing, proposed an unidimensional expression (Eq. 2), which relate the scaled transport distance as function of the scaled grain sizes:

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| --- | --- | --- |
|  |  | (2) |

where *L* is the transport distance of tracer with diameter *D*, while *LD50* is the mean transport distance exhibited by the median surface grain size (*D50*). Due to the use of surface *D50* instead of sub-surface *D50* suggested by Church and Hassan (1992), in this work the scaled grain size was multiplied by 2.2 following Wilcock (1997) and Vázquez-Tarrío and Menéndez-Duarte (2014).

The determination of the critical discharge and the transport distance enabled to estimate the virtual velocity (*Vv*) expressed by each tracer during the intra-survey periods. Precisely, *Vv*was calculated as ratio between the transport distance exhibited by the tracer and the competent flow duration. This latter was considered as the over-threshold flow duration experienced by the corresponding tracer size class during the intra-survey period. In each of these periods, the mean virtual velocity (*Vvm*)was calculated as the arithmetic mean of the individual *Vv*, accounting also the not mobilized tracers (Gintz el al., 1996; Houbrechts et al., 2015). Consistently with what was done for the transport distance, also for the bedload propagation velocity the relationships with hydraulic forcing conditions and tracer sizes were investigated. As regards this latter, Ferguson and Wathen (1998) analyzing the bedload mobility in the Allt Dubhaig (Scotland) observed that the unidimensional virtual velocity (*V\**) can be controlled by relative grain size (*D\*)* obtainable by the Eq. 3 and 4, respectively:

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

where *Vi* is the mean virtual velocity expressed by size fraction *i*, *g* the gravity acceleration and *D* is the tracer diameter, while:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

where *D50* is the median size of streambed surficial grain size. Therefore, the *V\**- *D\** relationship permits to analyze the influence of the tracer diameter and the median diameter of the surrounding particles on the virtual velocity (Ferguson and Wathen, 1998; Milan, 2013). To define *D\**, Church and Hassan (1992) suggested to use sub-surface *D50*,since the bedload grain size distribution commonly appears more similar to the sub-surface streambed material. Instead, in this work the surface *D50* was used to scale tracers following Ferguson and Wathen (1998), thus allowing to consider even the hiding and protrusion effect acted by the surface material on the bedload propagation velocity.

1. **RESULTS**
   1. **Tracer inventories**

Between May 2012 and October 2018, 14 tracer inventories were conducted, defining the corresponding intra-survey periods (P1 to P14). Of these, 6 exhibited flow regimes dominated by rainfall-driven events (R), while snowmelt-induced flows (S) and mixed-nature flows (M) prevailed in 4 intra-survey periods each (Table 2). During the study period, the peak of water discharge (*Qp*) ranged between 0.44 and 2.10 m3 s-1, i.e., among under- and near-bankfull flow conditions (*Qbf* = 2.30 m3 s-1). Specifically, the highest *Qp* was observed during P1, while the lowest in P7 (Table 2). In terms of mean water discharge (*Qmean*), the higher and lower values were recorded in P5 and P3, respectively. If *Qmedian* is considered, the higher and lower values correspond to P5 and P4, respectively. The minimum *Qp* for which the tracers mobility was observed was 0.44 m3 s-1 (Table 2), which was then assumed to represent the critical discharge for the initiation of tracers motion (*Qc*). In this sense, long over-threshold times (*tover*) were recorded during the periods P2 and P13, which represent extended time intervals including snowmelt (Table 2). Conversely, *tover* is smaller in summer periods P3 and P7. As expected, the values of effective runoff volume (*ER*) tend to increase with *tover* but with an important *ER* registered even in P5, suggesting a short intra-survey period characterized by a high runoff due to a rain-on-snow flood event (Table 2). In the inventories, the recovery rate of the tracers (*Rr*) was always higher than 45%, with an average value of nearly 60%. The lowest *Rr* was obtained during the third inventory (14 October 2013) due to technical issue with the RFID antenna. Similar problems might have affected also the previous survey (25 July 2013).

### Table 2 ###

* 1. **Thresholds of motion**

The flow competence method and tracers mobility were used to quantify the critical discharge (*Qci*) for the motion of each grain size traced (*i*). The tracer inventories show that the minimum *Qp* that caused tracers displacement was equal to 0.44 m3 s-1 (Table 2). Specifically, this critical discharge was able to mobilize the finer tracer size classes 45.3 and 64.0 mm. Instead, the classes 90.5, 128.0, 181.0 and 256.0 mm were entrained when *Qci* ≥ 0.72, 0.83, 1.09 and 2.06 m3 s-1,respectively. Interestingly, the critical condition at which all tracer classes were mobilized (*Qci* ≥ 2.06 m3 s-1) occurred only for 0.01% (i.e., 6 hours) of the study period. Fig. 3a shows the relationship between the critical unit water discharge (*qci*) and the particle grain size (*Di*), defined by both tracer mobility (flow competence) and flood competence. This relationship was compared with the thresholds estimated by Lenzi et al. (2006a) in the Rio Cordon during 1993-1998, by using painted and active radio-tracers and flood competence. The corresponding regression lines plot quite similarly with no statistically significant differences in terms of intercept (ANOVA, p value = 0.422) and slope (ANOVA, p value = 0.146). However, it is interesting to note how during 2012-2018 the particle sizes were mobilized by a slightly lower *qci*, a trend that decreases with increasing *Di*. In fact, the 2012-2018 relationship showed a higher exponent *b*, and a steeper slope.

### Fig. 3 ###

If the critical conditions are expressed in terms of critical stream power (*ωci*; Fig. 3b) data obtained in the Rio Cordon during 2012-2018 clearly plot at higher values if compared with what observed in other study sites, suggesting higher *ωci* for the initiation of motion. In particular, *ωci* differs approximately of an order of magnitude for particle diameters < 100 mm. If compared with the relationship determined in the Rio Cordon during 1993-1998 (Mao et al., 2008), the results appear consistent with what observed in Fig. 3a, i.e., *ωci* slightly lower and a fitted relationship characterized by a higher exponent. It is interesting to note that the streams compared here are different in terms of channel gradient (*s*), being mild in the Ardenne rivers (0.002 – 0.009 m m-1), higher in the Carpathians (0.10 m m-1), and even higher in the Rio Cordon 1993-1998 (0.14 m m-1) and 2012-2018 (0.13 m m-1). This lead to a difference in the the relationships *ωci* = *a Dib* , with an increase in coefficient *a* and a decrease of exponent *b* with increasing *S* (Fig. 3b).

* 1. **Transport distance**

Between the intra-survey periods, the mean transport distance (*Lm*) expressed by the tracers showed a large variability, spanning over three orders of magnitude (Table 2). The maximum displacement measured in the field was 322 m (*D* = 50 mm), during the period P5. According to the one-way ANOVA, the mean transport distance resulted not statistically different between the R, S and M flow regimes (F2,11 = 0.67, p value > 0.05). Among the variables calculated to describe the hydraulic forcing conditions, *Lm* exhibited the strongest power law relationship with *Qp* but even *qp* and *ωp* – *ωc* showed high coefficient of determination (R2) and statistical significant correlations (Table 3). Also *Qmean* appeared statistically correlated to the mean transport distance, but by lower R2. Conversely, *Qmed*, *tover* and *ER* exhibited low performances to describe *Lm*.

### Table 3 ###

Besides the hydraulic forcing conditions, also the influence of the tracer sizes on their displacement was investigated. In this regard, each scaled transport distance (*L*/*LD50*) was related to the relative scaled particle size (*D*/*D50*). Fig. 4a shows that all individual displacements tend to decrease with grain size, with the six tracer size classes showing a mean scaled travel distances that roughly follow Equation 2 proposed by Church and Hassan (1992). Then, during the study period, the transport distance seems to have been influenced by the tracer size, exhibiting a progressive reduction in size classes gradually coarser than the streambed *D50*.

### Fig. 4 ###

The relationship between the tracer size classes (*Di*) and the corresponding mean transport distance (*Li*) was investigated by grouping the intra-survey periods according to the magnitude expressed by *Qp*. Specifically, the intra-survey periods were classified as High (H) if *Qp***>** 1.50 m3 s-1, Medium (M) when 1.00 < *Qp* < 1.50 m3 s-1 and Low (L) with *Qp* < 1.00 m3 s-1. Using one-way ANOVA analysis, *Qp* resulted significantly different between these groups (F2,11 = 94.28, p value < 0.05). Fig. 4b shows that the fractional transport distances varied with the *Qp* of the intra-survey periods. In fact, mean transport distance increases by two order of magnitude passing from the L and M groups to the H one. The one-way ANOVA proved that such differences in *Li* among the three groups were statistically significant (F2,11 = 6.13, p value < 0.05). Besides the transport distance, H – M – L seems to show even different transport dynamics. In the L-periods, a progressive reduction of *Li* with increasing tracer size can be observed, suggesting size selective transport. Such behavior cannot be observed in the H-periods, where *Li* remains nearly constant in all the tracer sizes, collapsing only in the class 256 mm. Then, in the H-periods the tracers seem to have been mobilized under equal-mobility conditions. In the M-periods a clear transport dynamic cannot be observed, with scattered fractional transport distances. Interestingly, also the variability in the individual displacement (standard errors) decreases moving from L and M groups to the H one.

The fractional transport distances were compared to those observed in the Rio Cordon during 1993-1998 by Mao and Lenzi (2007). On the one hand, the L- and M- periods exhibited lower *Li* than those noted by the abovementioned authors for similar hydraulic forcing conditions (Fig. 5a). Particularly, the L-group (*Qp* < 1.00 m3 s-1) showed mean transport distance one order of magnitude lower than what reported by Mao and Lenzi (2007) for *Qp* = 0.87 m3 s-1. Despite this difference, the transport dynamic appears analogous, with reduced *Li* with increasing tracer size. On the other hand, the H-group showed higher transport distance than reported in 1993-1998 for comparable hydraulic forcing. In fact, during the H-periods (*Qp* > 1.50 m3 s-1) the tracers exhibited *Li* higher than those determined by Mao and Lenzi (2007) as consequence of *Qp* = 2.96 m3 s-1 and fully comparable to the *Li* estimated by the same authors for *Qp* = 4.28 m3 s-1, i.e., a peak discharge two fold greater than that accounted in H-group (Fig. 5a). Also, in the H-group the transport dynamic is similar to the ones observed by Mao and Lenzi (2007) for their higher hydraulic forcing conditions, i.e., mean displacements weakly dependent by the tracer size.

### Fig. 5 ###

As reported in Table 3, the *Lm* recorded during the intra-survey periods resulted statistically correlated to the excess of stream power(*ωp* -*ωc*). The relationship estimated for the Rio Cordon during 2012-2018 is clearly steeper than other proposals from the literature, with a steeper exponent *b* (Fig. 5b). In the Rio Cordon, this result seems to suggest that the increase of *ωp* -*ωc* triggered a strong increase in *Lm*, emphasizing an accentuate over-threshold mobility, greater than what observed in the other study sites. At similar values of *ωp* -*ωc*, the Rio Cordon features shorter *Lm* that the other sites. For instance at *ωp* -*ωc* ~ 100 W m-2 the mean transport distance is one order of magnitude lower than what observed in Wood Brook Creek (Dudley, 2007) and in the Rio Cordon during 1993-1998 (Lenzi, 2004), and two order of magnitude lower than the *Lm* estimated in Lainbach Stream (Gintz et al., 1996) and Erlenbach Stream (Schneider et al., 2014). The steeper scaling exponent characterizing the relationship estimated in the Rio Cordon during 2012-2018 caused that such difference decreases with increasing the excess stream power.

The 7-year sediment mobility investigation also enabled to assess the existence of possible trends exhibited by the measured variables over the study period. To this end, the Mann-Kendall (MK) non-parametric test was used (Kendall, 1962). Fig. 6 shows the temporal variability of that *Lm* over the 14 intra-survey periods, classifying the periods in H, M and L group. From this analysis the intra-survey period P2 was excluded, because H-period probably affected by underestimation of mean transport distance (see section 3.1). According to the MK test, over the study period, the mean transport distance exhibited a negative but not statistically significant trend (S = - 29.0, p value = 0.112). This result is in line with what showed by *Qp*, which, however, was characterized by a clearly gentler decrease over time (S = - 8.0, p value = 0.661). The decline in *Lm* is evident even within each group considered, with the highest mean transport distance recorded in the respective first intra-survey periods, i.e., P1 (H), P4 (M) and P3 (L). Interestingly, the H-periods exhibited a constant and progressive reduction, with a decrease in *Lm* equal to - 5% between P1-P5, - 23 % among P5-P8, and - 95% amid P8-P13. In the M- and L-periods the *Lm* decline is clear over the long term, i.e., - 95% between P3-P10 (L-periods) and - 63% among P4-P14 (M-periods) but either exhibited a more scatter trend compared to what observed in the H-group. In fact, in the L-periods, an increase of *Lm* between P7-P9 (+ 201%) can be appreciated. Similarly, the mean transport distance increases between the M-periods P12 and P14 (+ 85%). Interestingly, in both cases, the intra-survey periods were not consecutive but interspersed with an H-period, i.e., P8 e P13, respectively. Differently, successive L- and M-periods showed a clear decrement of *Lm*. This behavior is clearly evident between P6-P7 (- 88%), P9-P10 (- 67%) and P11-P12 (- 43%).

### Fig. 6 ###

* 1. **Virtual velocity**

The obtained mean virtual velocity (*Vvm*) showed a large variability between the intra-survey periods, by spanning over three orders of magnitude, i.e., between 0.001 and 0.723 m h-1 (Table 2). The maximum virtual velocity observed was equal to 21.3 m h-1 (*D* = 190 mm), for the period P8. Among the R, S and M flow regimes, the mean virtual velocity was found to be not statistically different (F2,11 = 1.25, p value > 0.05). In describing *Vvm*, significant power law correlations were expressed by *ωp* - *ωc*, *Qp* and *qp*.Conversely, low performances were manifested in particular by *tover* and *ER* (Table 4).

### Table 4 ###

The relationship between unidimensional virtual velocity (*V\**) and relative tracer size (*D\*)* was analyzed, allowing to determine if the tracer size and the median diameter of surrounding particles influenced the virtual velocity. The *V\** - *D\** relationship, determined for each tracer size class, resulted statistically significant (R2 = 0.667, p value < 0.05), revealing that the virtual velocity increased with coarsening of tracer size (Fig. 7a). Particularly, the *V\** - *D\** relationship seems to suggest that the higher bedload propagation velocity was expressed by the tracer size classes coarser than the median diameter of surrounding particles, i.e., larger than the *D50* of streambed surficial grain size (*D\** > 1).

### Fig. 7 ###

As reported in Table 4, the relationship between the excess of stream power (*ωp* -*ωc*) and the mean virtual velocity (*Vvm*) can be expressed with a statistically significant power law regression. Fig. 7b shows that the Rio Cordon featured lower virtual velocities if compared with other study sites. Particularly, for a *ωp* -*ωc* ~ 100 W m-2 the velocity propagation appeared about one order of magnitude lower if compared to what observed in the Spuce Creek (Lamarre and Roy, 2008) and of two orders of magnitude respect to the Ardenne rivers (Houbrechts et al., 2015). Such difference reaches three orders of magnitude when compared to the results achieved by Hassan et al. (1992) and Gintz et al. (1996) in riffle-pool channels and Lainbach Stream, respectively. In line to what observed for the transport distance, the relationship between *ωp* -*ωc* and *Vvm* resulted characterized by a steeper exponent *b* (Fig. 7b). Consequently, the increase of *ωp* -*ωc* causes a reduction in the difference between Rio Cordon and the other study sites, with bedload propagation velocities that come progressively closer to what observed in the Spruce Creek. Unlike for the transport distance, in the virtual velocity none clear tendency is observable over the study period.

1. **DISCUSSION**
   1. **Field observations**

Sediment mobility was investigated over 7-years by particle tracing in the Rio Cordon, over a period characterized by a range of hydraulic forcing conditions, i.e., snowmelt, rain-on-snow events, summer storms, convective rainfalls, persistent autumnal precipitations and drought periods (Table 2). Despite a certain variability between the intra-survey periods, the hydraulic forcing conditions were constantly under- or near-bankfull (Fig. 2). Hence, the sediment mobility was investigated during high frequency flows, i.e. for conditions close to the effective and dominant discharges, which represent the discharges that in the fluvial systems mostly control sediment fluxes and morphological setting (Benson and Thomas, 1966; Downs et al., 2016). In the Rio Cordon, the bedload tracing has proved to be a valuable method to analyze, over the long-term, the mobility of the streambed coarse material. Overall, the analysis was based on 14 inventories with 1697 tracer localizations and 528 displacements longer than 1 m. During the monitoring program, the main problem encountered was related to technical issues on RFID antenna, causing a partial study reach inspection during the second and third inventories. This may have led to a partial underestimation in the mobility observed in particular in the high magnitude period P2, by excluding the tracers transported furthest (frontrunners). However, during the 14 tracer inventories, *Rr* was constantly greater than 45%, with an average of nearly 60%, which is comparable with the recovery rates reported in similar works conducted in mountain streams by using RFID technology (Table 5).

# ### Table 5 ###

* 1. **Critical conditions for initiation of motion**

The hydraulic forcing conditions occurred during the study period caused the motion of the entire range of tracer size classes. In terms of critical conditions for initiation of motion, *Qci* ranged between 0.44 m3 s-1 for the finer classes (45.3 – 64.0 mm) to 2.06 m3 s-1 for the entrainment of class 256.0 mm. Then, the condition *Q >* 2.06 m3 s-1 triggered the motion of the entire range of tracers, which correspond to a large portion of Rio Cordon streambed material (*D20* - *D70*). The critical conditions (*qci*) resulted very close to those estimated in the Rio Cordon by Lenzi et al. (2006a). Interestingly, Lenzi et al. (2006a) analyzed the bedload mobility during the period 1993-1998, i.e., accounting also for the floods subsequent to the September 1994 high magnitude/low frequency event (Rainato et al., 2017). Such event (recurrence interval, *RI* > 30 years) caused the destruction of the bed armouring and the flattening of the protruding bedforms, leading to a considerable vertical exchange between surface and sub-surface material, reduction of form resistance and, then, an augmented transport efficiency in the following floods (Lenzi, 2001; Turowski et al., 2009; Zhang et al., 2020). Conversely, steady conditions of bed armouring and stable protruding bedforms (cascade/step-pool) characterized the period 2012-2018 (Mao et al., 2010; Rainato et al., 2017). Despite these diverse streambed configurations, no significant differences were observed in terms of the critical conditions between the two periods of bedload monitoring. However, it is worth bearing in mind that different approaches in the bedload tracing and in the definition of “entrainment” were used. Lenzi et al. (2006a) assumed as entrained a particle exhibiting a displacement lower than its diameter, while this work considered that such condition occurred when displacement is longer than 1 m. This methodological choice is consistent with other bedload mobility investigations (Haschenburger and Church, 1998; Houbrechts et al., 2015) and it is justified by the complex topography of the streambed of the Rio Cordon and the fact that a loop antenna was used to retrieve the tracers. The antenna allows to detect the presence of a tracer in a given area, but considering a particle entrained even with *L* < 1 m would likely lead to an underestimation of the critical conditions. This more “conservative” approach than chosen by Lenzi et al. (2006a) could be somewhat counterbalanced by the different tracers used. In fact, in this work the incipient motion was established using the RFID technology, which allows to identify with an alphanumeric code each particle, permitting a higher precision in the tracer detection, enabling to survey the buried tracers too (Lamarre et al., 2005; Chapuis et al., 2014). Conversely, the use of particles simply painted may have precluded Lenzi et al. (2006a) to investigate the tracers actually entrained in deep pools or incorporated in steps, conditions frequently observed in 2012-2018. Also, it is worth stressing that such dissimilarity regards only the critical conditions determined by the flow competence, while the component associated with the flood competence was consistently applied in the periods 1993-1998 and 2012-2018. Interestingly, the current *qci* - *Di* relationship fitted slightly steeper if compared to that one estimated in 1993-1998, with the power law exponent *b* that increase of 22%, suggesting conditions of more accentuated selective entrainment. This suggests that, in conjunction with the poorly sorted streambed material, in 2012-2018 even a certain particle embedding acted on the bedload mobility (Bathurst, 2013). However, the poorly sorted nature of streambed material produced hiding and protrusion effects that, in turn, caused that the exponent *b* remained distant from 1.5, which indicates a perfect size-selective behavior (Lenzi et al., 2006a).

The comparison with the critical conditions observed in other study sites confirmed that steep feature higher critical stream power for particle entrainment, mainly due to the higher energy dispersion caused by bedforms and by the relative macro-roughness (Wilcox et al., 2011; Schneider et al., 2014). If compared to fine-grained and gentler-gradient channels investigated in the Ardenne and Carpathians, the Rio Cordon exhibited higher *ωci* but with a flatter power law relationship (Fig. 3b). Then, the difference with Ardenne (Houbrechts et al, 2015) and Carpathians (Galia and Škarpich, 2016) decreases with increasing *Di*. Specifically, the Rio Cordon showed *ωci* greater than one order of magnitude for *Di* smaller than 100 mm, while the coarser particles resulted entrained by critical stream powers very close to those estimated in the milder channel gradients. This seems to suggest that slope and protruding bedforms acted mainly on the entrainment of the finer diameters, while the coarser fraction are mobilized by hydraulic forcing conditions under which slope and bedforms becomes progressively submerged and dissipate less energy. Zimmermann and Church (2001), Chin (2003) and Comiti et al. (2009) suggested that step-pool configuration can experience such dynamic under high flows, which cause bedforms submergence and water surface flattening. In such conditions, the thresholds observed in the Rio Cordon approaching those demanded in the streams of Ardenne and Carpathians, for the mobilization of the same coarser fraction, but along flatter gradients.

* 1. **Displacement length**

The range of mean transport distance (*Lm*) observed in the intra-survey periods is line with the displacements detected by other bedload mobility investigations (Table 5). Among the hydraulic forcing variables tested to describe *Lm*, the higher significance were expressed by the peaking ones, in particular a strong positive power law correlation with *Qp*,*qp* and *ωp* -*ωc* was detected, respectively. Conversely, the duration (*tover*) and the volume (*ER*) of the competent flow have not controlled the transport distance (Table 3). Opposite findings were observed by Vázquez-Tarrío and Menéndez-Duarte (2014) in the Narcea River, while the significance of the excess stream power in the prediction of the transport distance is consistent with what observed by Gintz et al. (1996), Lenzi (2004), Dudley (2007), Schneider et al. (2014) and Houbrechts et al. (2015). In addition to the hydraulic forcing conditions, the displacements recorded in the Rio Cordon were influenced also by the tracer sizes. Particularly, the progressive transport distance decrease with increasing tracer size class was resulted concordant to the hyperbolic expression proposed by Church and Hassan (1992). The combined influence of hydraulic forcing and tracer size on the displacement appeared evident in the analysis of the fractional transport distance that highlighted, on the one hand, a local (~ 1m) and size selective mobilization of the only finer tracer classes during the under-bankfull flow conditions (L- and M-group). On the other hand, the near-bankfull conditions (H-group) triggered an evident bedload transport in all tracer classes with equal mobility evidence (Ashworth and Ferguson, 1989). The fractional transport distances were compared to those estimated in the Rio Cordon by Mao and Lenzi (2007), highlighting different dynamics depending on the flow magnitude (Fig. 5a). Comparing the lower hydraulic forcing, the period 2012-2018 showed transport distances clearly shorter than those estimated in 1993-1998 by Mao and Lenzi (2007). Conversely, the near-bankfull flow conditions analyzed in 2012-2018 showed fractional displacements similar to those observed in 1993-1998 for discharges two times higher. These differences between the periods 1993-1998 and 2012-2018 could be explained by the hydraulic forcing conditions grouped, by the tracers used and by the bedforms setting. Precisely, the L-grouped clustered in 2012-2018 accounted 5 intra-survey periods characterized by *Qp* < 1.00m3 s-1 (largest *Qp* = 0.85m3 s-1), while the lowest hydraulic forcing considered by Mao and Lenzi (2007) corresponds to a single flood with *Qp* = 0.87m3 s-1. The relative higher mobility observed during the 2012-2018 in response to the near-bankfull flow conditions could be partly attributable by the different bedload tracing technique. During 1993-1998, Mao and Lenzi (2007) used mainly painted particles (430 painted clasts and 40 radiotracers) to investigate the sediment mobility and this type of tracers hamper a properly tracing of the frontrunners, since the probability to become buried increases with transport distance (Liébault et al., 2012). Hence, the displacements observed in 1993-1998 as response of the higher flood events might be affected by a certain underestimation due to the lacking detection and, thus, estimate of buried frontrunners. Also, the pronounced bedload mobility observed in 2012-2018 during the under-bankfull flow conditions seems to be consistent with the analysis of the critical conditions, suggesting an evident increase of transport efficiency during the higher flows. This behavior could be due to the reduction of form drag and macro-roughness caused by bedforms submergence (Comiti et al., 2009).

The significant power law relationship between excess stream power and mean transport distance allowed to compare the bedload mobility observed in the Rio Cordon with the transport rates detected in other study sites (Gintz et al., 1996; Lenzi, 2004; Dudley, 2007; Schneider et al., 2014). At similar values of *ωp* -*ωc*, the Rio Cordon featured lower values of *Lm* (Fig. 5b). If compared to the Lainbach Stream (*s* = 0.02 m m-1) and the Wood Brook Creek (*s* = 0.03 m m-1), the Rio Cordon presents a steeper gradient with coarser and poorly sorted streambed material, stressing that in the steep streams the bedload mobility is generally affected by a reduced efficiency due to form-drag and macro-roughness effects (Nitsche et al., 2011; Yager et al., 2012). Also, in the Lainbach Stream, Gintz et al. (1996) at every inventory repositioned the detected tracers along the release sections, precluding their incorporation in the streambed material. It is worth noticing that only tracers with *L* > 1 m were considered mobilized in the Rio Cordon during 2012-2018 which may have led to a conservative estimate of *Lm* although the use of the antenna likely improved the accuracy of the tracer retrieval. Compared to the Erlenbach Stream (*S* = 0.15 m m-1), the different transport distance seems to be mainly related to the hydraulic forcing conditions investigated. Differently from the Rio Cordon, in the Erlenbach Stream even large floods were analyzed during the study period (Schneider et al., 2014). Two events with, respectively, *RI* > 5 and *RI* > 10 years occurred, which may have increased the transport efficiency in the subsequent floods (Turowski et al., 2009). A similar dynamic may have influenced the Lainbach Stream since in the study period analyzed by Gintz et al. (1996) an extreme event occurred. Hydraulic forcing conditions, tracer size classes, bedload tracing technique and streambed configuration can help to explain the different relationships detected in the Rio Cordon (Fig. 5b). Lenzi (2004) monitored the period 1993-1998 by investigating 7 floods with *Qp* between 0.87-10.44 m3 s-1, of which 3 floods with *ωp* -*ωc* > 800 W m-2, and by tracing a larger grain size fraction than the range analyzed in 2012-2018 (Table 5). Thus, the wider range of excess stream power and tracer size classes considered in 1993-1998 may have caused that the relative power law relationship has settled on a minor slope. Additionally, Lenzi (2004) detected also larger *Lm* for equal terms of *ωp* -*ωc*. In this sense, it is worth noticing that the author investigated even the post-September 1994 floods, when the removal of armouring layer and alteration of protruding bedforms favored an increased transport efficiency. Conversely, under permanent and undisturbed conditions of well-developed armour layer and stable bedforms characterized the Rio Cordon in 2012-2018. Interestingly, the transport distances appeared similar to those estimated by Lenzi (2004) only for *ωp* -*ωc* > 400 W m-2, condition under which the not recovered painted frontrunners may have led to an underestimation of *Lm* and consequently a reduced exponent *b* in the 1993-1998 period.

The long-term investigation carried out in the Rio Cordon permitted to stressed that in the case of two consecutive intra-survey periods of equal magnitude, the second one always expressed lower mean transport distances (e.g., P6-P7, P9-P10 and P11-P12). Conversely, when the two intra-survey periods of equal magnitude were separated by a higher magnitude period, the second one showed higher *Lm* (e.g., P7-P9 and P12-P14). Despite the limited dataset, the results suggest the existence of a flood memory effect. In particular, the results obtained in the Rio Cordon seem to suggest that the sequence of periods characterized by different magnitude of events can influence the transport efficiency, likely by controlling the conditions under which each period leaves the surface sediment. As observed in flume experiments by Mao (2018), the second of two periods characterized by events of similar magnitude transport less sediments because the first leaves the streambed in less favorable conditions for sediment mobility. On the other hand, an event of a certain magnitude transports more sediments if it occurs after an event of higher magnitude rather than before, as the high magnitude event leaves an unstructured streambed.

Overall, during the 7 years-long study period, a general and progressive reduction in the transport distance was observed (Fig. 6). Interestingly, *Lm* exhibited a not significant trend but the decrease was more marked than those observed in *Qp*, suggesting that the reduction in the mean transport distance cannot be explained by the mere reduction of the peak discharges overtime. The decrease of *Lm* also appears when one takes into consideration periods characterized by similar magnitudes (i.e., H, M, L). In this sense, the transport distance reduction was particularly clear in the fully comparable periods P5-P8, P6-P9 and P4-P12. Several studies demonstrated that, in the long run, bedload tracing shows a reduction in the sediment mobility due to the progressive deposition of tracers in preferential storage sites as riffles, bars, steps and pools (Petit, 1987; Powell, 1998; Houbrechts et al., 2015; Vázquez-Tarrío et al., 2019). However, the reduction documented in the Rio Cordon could be due also to the succession of under- and near-bankfull flow conditions that caused a progressive stabilization of sediment in the channel and a reinforcement of sediment clusters, producing a legacy on the sediment mobility resulting in a decreasing transport efficiency over the study period. Such hypothesis is in line to what observed in the Erlenbach Stream by Masteller et al. (2019), who demonstrated that the channel stabilization and local rearrangements caused by a sequence of low magnitude flows (and time without transport) led to an increment on the critical conditions for initiation of motion. The authors stated that such “history dependence” can be removed by large events. The dataset collected in the Rio Cordon during 2012-2018 did not account for a high magnitude floods but in light of studies previously realized in the site, it seems that the flood events act on different spatial and temporal scales depending on their magnitude. Particularly:

1. the high magnitude/low frequency events (*RI* > 30 years), it has been proved, that in the Rio Cordon acted at basin-scale and over the long-term, by a wide alteration of sediment source areas and channel configuration and, thus, augmenting the transport efficiency for decades (Rainato et al., 2017; Pagano et al., 2019);
2. the over-bankfull floods (1.5 < *RI* < 30 years) mainly resulted in the formation of limited sediment sources and by increasing the transport efficiency at event-scale (Lenzi et al., 2004);
3. the results of this study seem to suggest that also the under- and near-bankfull events influenced the sediment dynamics, by acting at reduced spatial- and temporal-scales, i.e., on the channel network by creating a certain legacy on the transport efficiency of subsequent floods. As demonstrated by the abovementioned authors, such legacy can be interrupted by high magnitude/low frequency events.

* 1. **Propagation velocity**

The *Vvm* observed in the intra-survey periods appeared relatively low compared to the virtual velocities estimated in other bedload mobility investigations (Table 5). The relative slow bedload propagation velocity detected in the Rio Cordon could be explained, in part, by the energy dissipation and trapping effect relate to the stable and protruding bedforms (Haschenburger, 2011; Hassan and Bradley, 2017; Vázquez-Tarrío et al., 2019). Also, differently than Gintz et al. (1996), the detected tracers were not repositioned but were left to mix in the streambed configuration. This can led to a progressive slowdown over the long-term (Ferguson et al., 2002; Ferguson and Hoey, 2002). Interestingly, *Vvm* exhibited the stronger power law correlations with *Qp*,*qp* and *ωp* -*ωc*, while duration or volume of the competent flow resulted not statistically significant in describing the bedload propagation velocity over the intra-survey periods. This result is consistent with the findings obtained by analyzing the transport distance analysis, suggesting that during the study period the bedload mobility was mainly controlled by the magnitude expressed by the peak discharge. However, the relationships obtained for the virtual velocity exhibited general lower performances compared to the transport distance (Table 4). This could be due to the fact that the virtual velocity is the result of the ratio between displacement exhibited by the tracer and the corresponding over-threshold flow duration, and each of these factors introduced a relative bias (Houbrechts et al., 2015). This implicit uncertainty may have precluded the observation of tendency in the virtual velocity.

The transport distance and virtual velocity appear to be unaffected by the typology of dominant flow regime (R, S and M). Nevertheless, it is worth noting that the intra-survey periods dominated by rainfall-driven flows exhibited an average virtual velocity of 0.213 m h-1, i.e., one- and two-order of magnitude higher than what observed, respectively, in the intra-survey periods dominated by mixed-nature flows (average *Vvm* = 0.071 m h-1) and snowmelt-induced flows (average *Vvm* = 0.006 m h-1). This finding is consistent with what observed in the Upper Strimm Creek by Dell’Agnese et al. (2015). However, it is worth remembering that, in the Rio Cordon, the difference between the R, S and M proved to be statistically not significant.

As also observed in the transport distance, the virtual velocity is influenced by the tracer size. The relationship *V\** - *D\** was statistically significant and, interestingly, showed an increase of unidimensional virtual velocity with increasing relative tracer size. In the literature, only few authors explored such relationship. Ferguson and Wathen (1998) introduced it to investigate the sediment mobility in the Allt Dubhaig, observing a progressive decrease of the bedload propagation velocity with increasing tracer sizes. Conversely, Milan (2013) detected a positive trend in the Rede River, ascribing it, at least partially, to an underestimation of the displacement in the finer tracer size classes due to their burying and mainly to finer tracer sizes mobilized over large distance by long competent durations, opposite to the coarser sizes transported only during specific large events. Evidence from the Rio Cordon seem to support such hypothesis, in fact, the coarser tracer classes (*D\** > 1) were mobilized only by discharges > 1.09 m3 s-1, i.e., a condition that occurred merely in the 1.25 % of the hours analyzed. Also, it is interesting to note that both Rio Cordon and Rede River were investigated during near- or under-bankfull flow conditions with stable armouring layer, while Ferguson and Wathen (1998) analyzed the Allt Dubhaig during frequent over-bankfull floods and with no armouring. In light of this, the trend exhibited by the *V\** - *D\** relationship seems to be somehow influenced by the hydraulic forcing conditions experienced by the tracers and by the streambed configuration. Particularly, in the Rio Cordon the virtual velocity seems to be affected by the transport efficiency limitation due to the stable and protruding bedforms that, during near- and under-bankfull flow conditions, results in a sharp slowdown of the *Vv* expressed by the tracer sizes finer than the surficial D50 (*D\** < 1). Consistently to what observed by Hassan et al. (1992), Gintz et al. (1996), Lamarre and Roy (2008) and Houbrechts et al (2015), the relationship between excess stream power and mean virtual velocity resulted to be statistically significant but, in line to what noted for the transport distance, the Rio Cordon, on equal terms of *ωp* -*ωc*, demonstrated lower *Vvm*. The difference is particularly evident for excess stream power ~ 100 W m-2. As was for *Lm*, also the lower virtual velocity might be explained by the hydraulic characteristics of study period and by the geomorphic setting of study site. In fact, both in the Lainbach Stream (Gintz et al., 1996) and in the Ardennian gravel bed rivers (Houbrechts et al., 2015) the virtual velocity was estimated with gentler gradient and during time intervals with flood events largely over the bankfull condition, which can led to an accentuate transport efficiency over the study period. Also, Gintz e al. (1996) replaced the detected tracers at every inventory. Conversely, Lamarre and Roy (2008) analyzed conditions very similar to those investigated in the Rio Cordon. The Spruce Creek was characterized by *s* = 0.14 m m-1, stable step-pool configuration, rough streambed dominated by pebbles and boulders (*D50* = 160 mm) with a study period which consisted mainly in near- and under-bankfull floods. In this sense, the relationship fitted in the Rio Cordon (Fig. 7) appears steeper that the one described for the Spruce Creek, showing virtual velocities that progressively approach for *ωp* -*ωc* > 300 W m-2. Hence, also the bedload propagation velocity seems to be consistent to a reduced transport efficiency in the steep channels likely due to an important energy dissipation (macro-roughness, form drag, imbrication effect). Such hypothesis seems to be supported even by the steep scaling relationship estimated in the Rio Cordon, which suggest that such disturbance on the bedload propagation velocity decreased with increasing excess stream power, i.e., under conditions in which the bedforms reduce their influence due to their submergence and, then, by a water surface flattening.

1. **CONCLUSIONS**

Although it is a crucial component of fluvial systems, the dynamics that control bedload mobility were rarely investigated and, hence, they were only partly understood. This study analyzed the bedload mobility in the Rio Cordon mountain stream, by a tracing investigation maintained over 7 years. During the study period (2012-2018), the tracers experienced persistent high frequency/low magnitude flow conditions. Under such conditions, transport distance and virtual velocity expressed by the tracers showed significant correlations with *Qp*,*qp* and *ωp* -*ωc*, stressing out that the bedload dispersion was mainly controlled by the magnitude expressed by the peak discharge. The tracer grain size demonstrated an ambivalent influence on bedload mobility. On one hand, the transport distance showed a decrease with increasing tracer sizes while, on the other hand, an opposite dynamic was observed in the virtual velocity. This result seems to suggest that, under the high frequency flows, the coarser tracers were mobilized by short and impulsive flood events, while the finer particles were transported by long competent duration. Compared to other study sites, the Rio Cordon exhibited higher critical conditions for initiation of motion with lower transport distance and virtual velocity. This is consistent with the sediment dynamics observed in the steep mountain streams, where the pronounced energy dissipation due to the macro-roughness and protruding bedforms can reduce the transport efficiency. Such disturbance seems to affect the Rio Cordon especially during under-bankfull flow conditions, while with near-bankfull flows the bedload mobility approach those observed in the other study sites, stressing a lower energy dispersion during these hydraulic forcing conditions.

The results obtained in the period 2012-2018 were compared to the bedload mobility observed in the Rio Cordon during 1993-1998. This permitted us to quantitatively assess how the bedload dispersion changed between a condition of stable armouring layer and protruding bedforms (2012-2018) and a streambed configuration with partial alteration of them (1993-1998). The presence of protruding bedforms and well-developed armour layer mainly influenced the transport distance that, on equal terms of excess stream power, resulted clearly lower. Conversely, the different streambed configuration seems to have not influenced the threshold for initiation of motion.

The long-term analysis permitted to observe that a sort of flood memory effect acted over the 7 years in the bedload mobility. In fact, a progressive reduction in the transport distance was evident over the study period, suggesting that the persistence of high frequency flow conditions can have arrange the bed material in less favorable conditions for the sediment mobility and progressively consolidate the streambed.

In mountain stream, field investigations of bedload mobility are infrequent and rarely maintained over long-term periods. Based on a monitoring program that lasted 7 years, this study permitted to analyze how critical conditions for initiation of motion, transport distance and virtual velocity responded to persistent high-frequency/low-magnitude flow conditions and their relationship with the particle size. Therefore, the results enabled to better comprehend the bedload dynamics induced by hydraulic conditions close to the effective and dominant discharges, which control the fluvial system over long-term. The complex field activities required to monitor tracers mobility along the steep and rough Rio Cordon may include a certain degree of uncertainty, although the use of RFID techniques improved the recovery rate and precision in the identification of the tracers in the field. In the near future, it will be interesting to maintain and pursue the bedload tracing in this and other study sites, in order to further analyze and better comprehend the mobility dynamics triggered by a wider range of hydraulic forcing.

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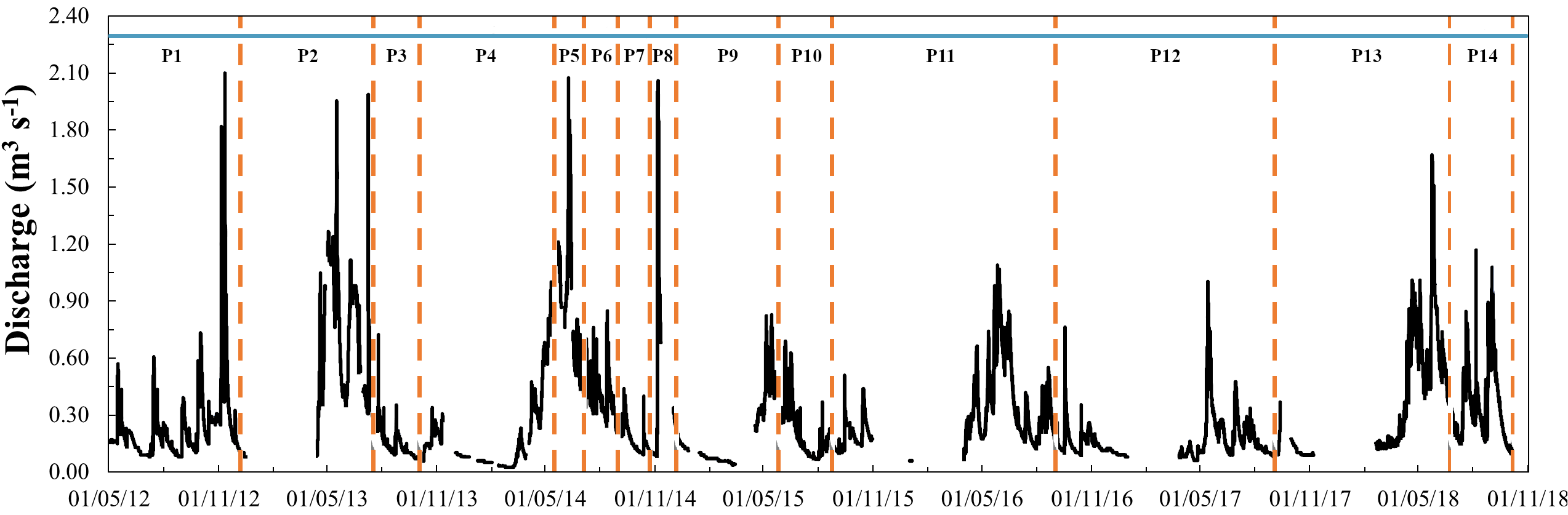
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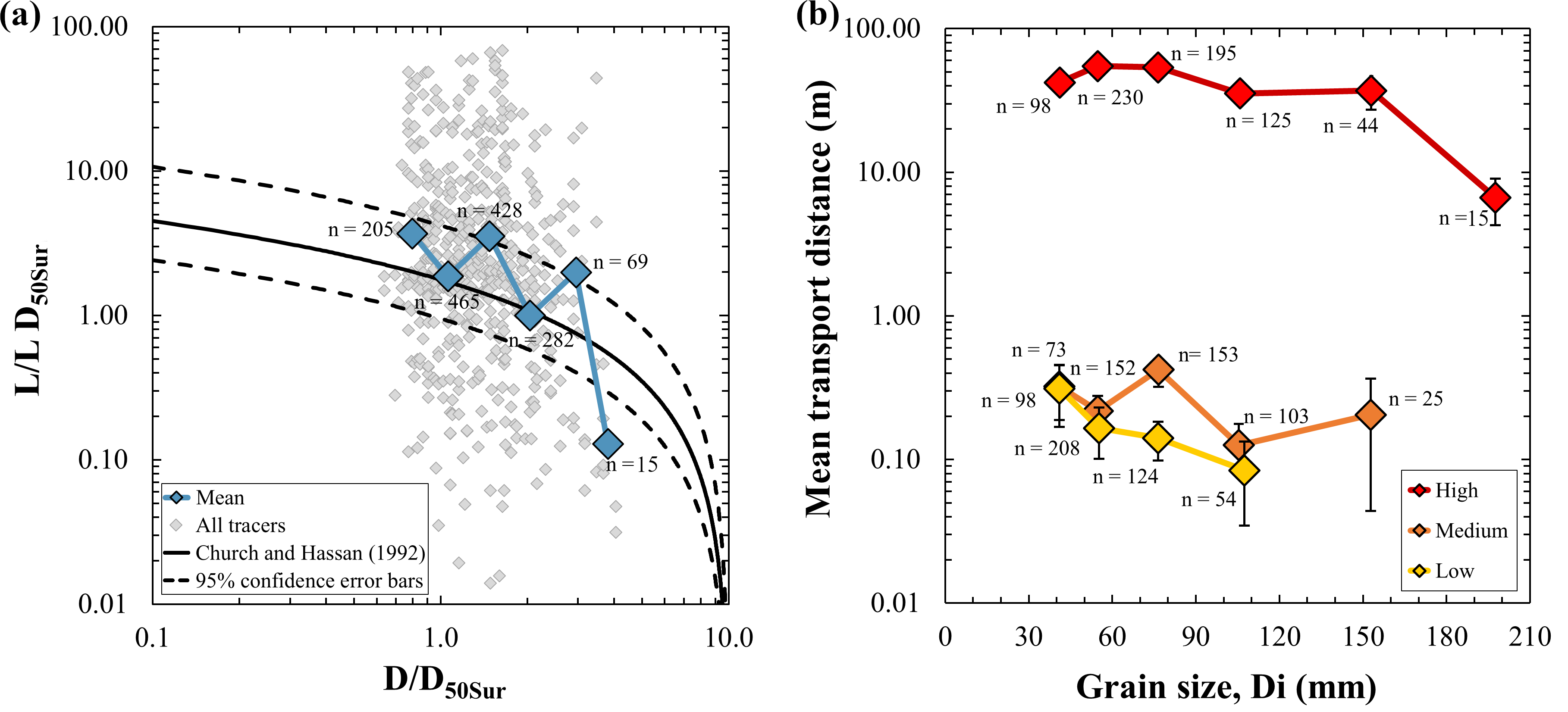
**Fig. 1.** (a) Rio Cordon basin and study reach equipped for the investigation of bedload mobility, (b) longitudinal profile of the study reach, (c) and (d) upper and lower part of segment analyzed.



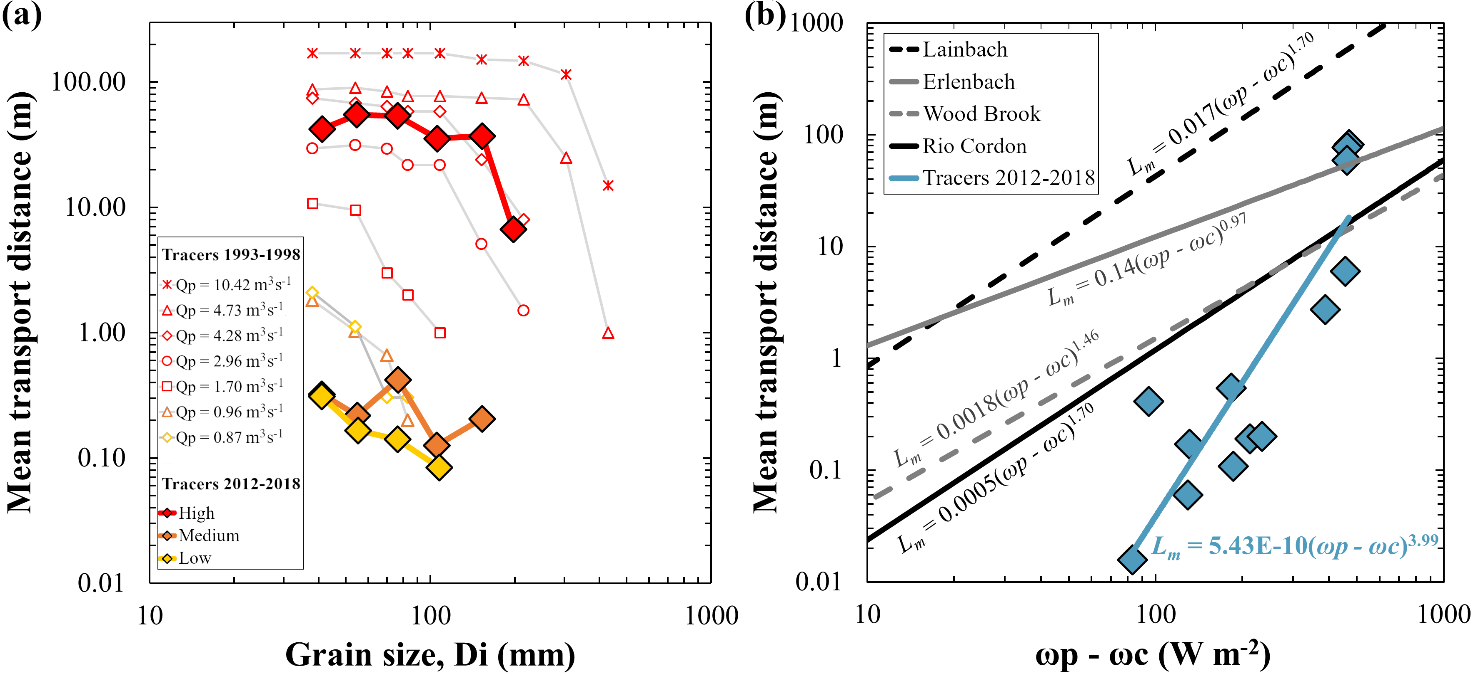
**Fig. 2.** Water discharge recorded by the Rio Cordon monitoring station during the study period (May 2012 – October 2018). The horizontal blue line express the bankfull discharge (Qbf = 2.30 m3 s-1), the orange vertical dashed lines represent the PIT inventories, while P1 – P14 identify the intra-survey periods.

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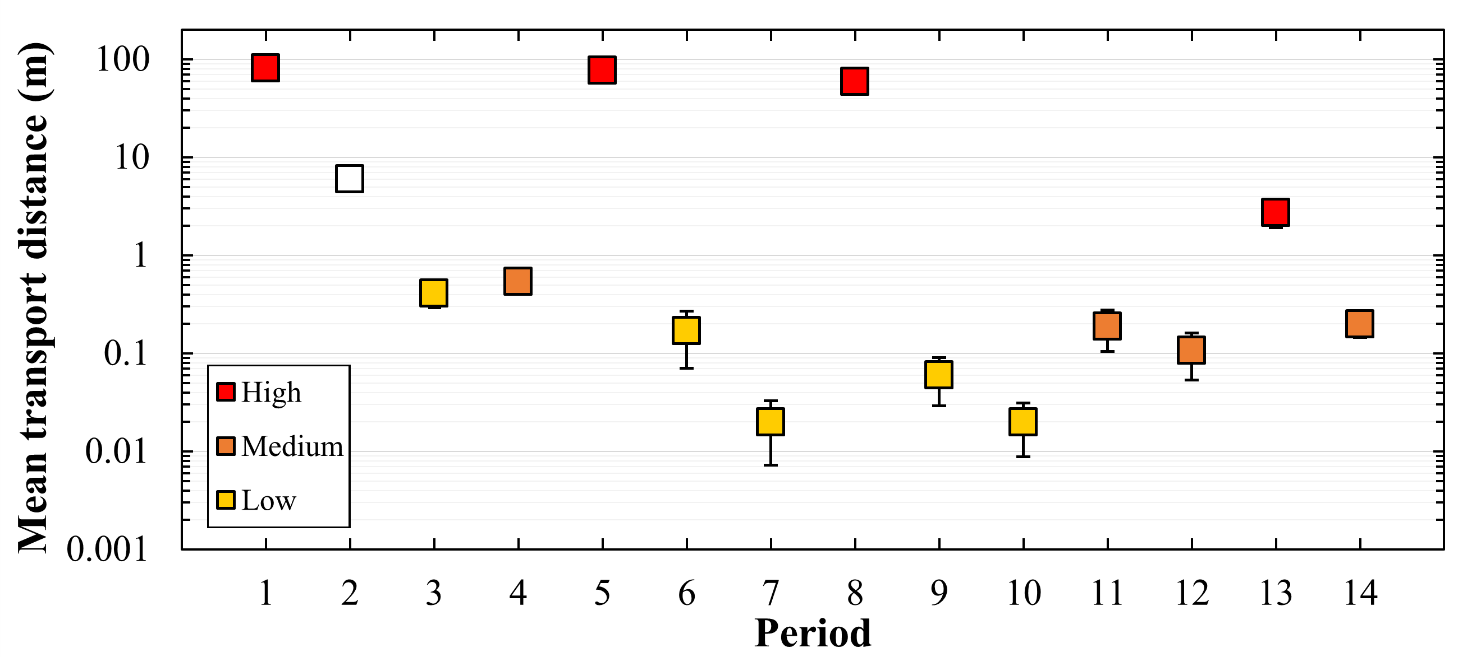
**Fig. 3.** (a) Relationships between critical unit water discharge (qci) and particle size (Di) observed in Rio Cordon, by combining flow competence (“Tracers”) and flood competence (“Floods”) methods. The grey and white squares are the data collected during the period 1993-1998 by Lenzi et al. (2006a), while the blue diamonds are the data collected during the period 2012-2018; the solid lines are the respective best-fit lines. (b) Relationships between critical stream power (ωci) and particle diameter (Di). Blue diamonds are the Rio Cordon data during the period 2012-2018 by combining flow competence (“Tracers”) and flood competence (“Floods”) methods and the solid line is the best-fit line. This was compared to the relationships observed in Rio Cordon during the period 1993-1998 (Mao et al., 2008), western Carpathians (Galia and Škarpich, 2016) and Ardenne rivers (Houbrechts et al., 2015).



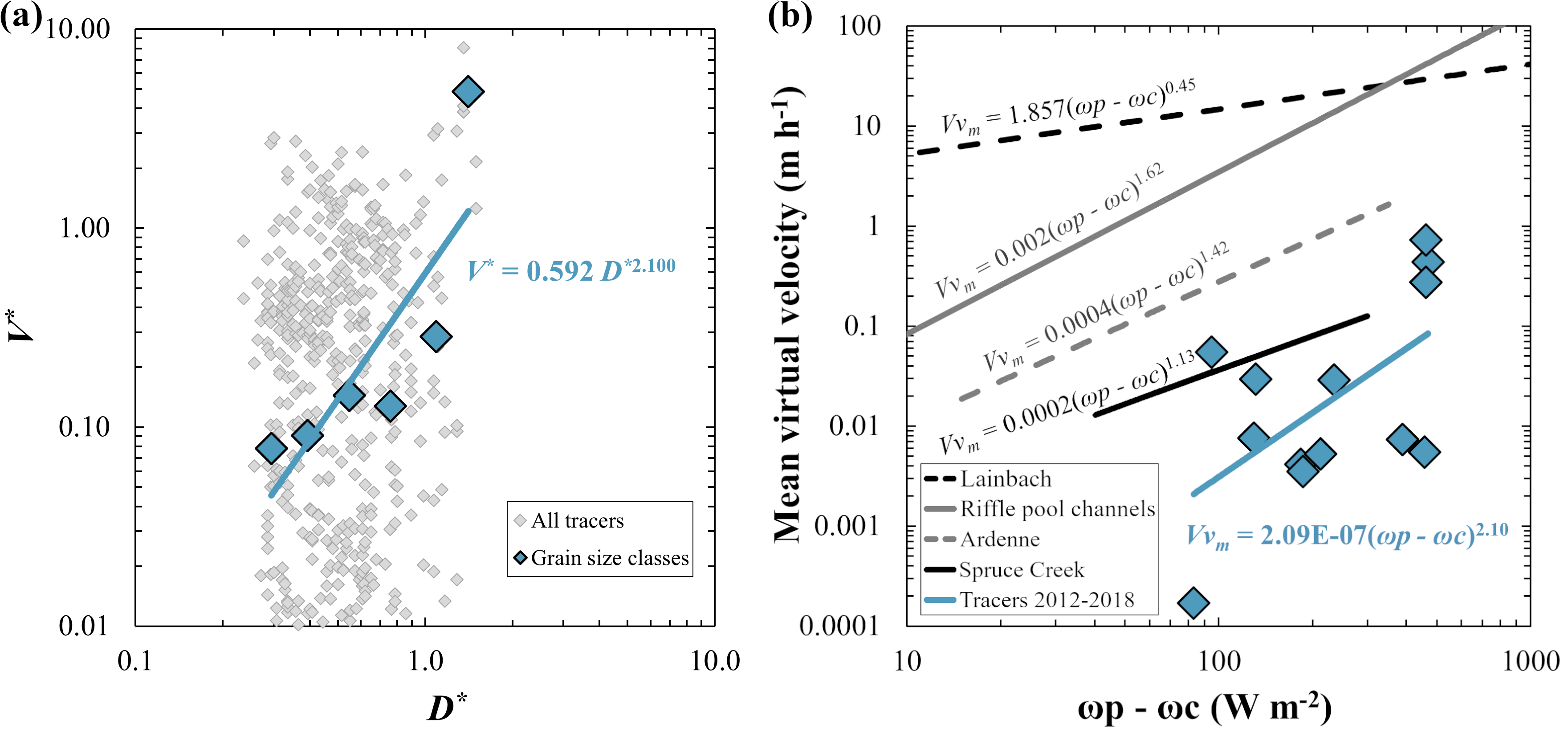
**Fig. 4.** (a) Relationship between scaled travel distance and scaled particle size for all individual displacements, with their mean in the six tracer size classes traced (blue diamonds); the relation is compared to the equation given by Church and Hassan (1992). (b) Relationship between mean travel distances (Lm), with standard errors, and the six tracer size classes traced (45.3 – 256.0 mm), for three magnitude groups.



**Fig. 5.** (a) Comparison among the relationship between mean travel distances and tracer size classes observed in this work and the relations observed in the Rio Cordon by Mao and Lenzi (2007). (b) Relationship between mean transport distance (Lm) and excess stream power (ωp -ωc) measured in the intra-survey periods. Blue diamonds are the Rio Cordon data during the period 2012-2018 and the solid line is the best-fit line. This was compared to the relationships observed in Lainbach Stream (Gintz et al., 1996), Erlenbach Stream (Schneider et al., 2014), Wood Brook Creek (Dudley, 2007) and Rio Cordon during the period 1993-1998 (Lenzi, 2004).



**Fig. 6.** Trend exhibited by the transport distance over the 14 intra-survey periods analyzed. The intra-survey periods were classified in H, M and L group, based to the magnitude expressed by Qp. P2 was excluded from this analysis as probably affected by underestimation of Lm (see section 3.1). Error bars indicate standard errors.



**Fig. 7.** (a) Variation of dimensionless virtual velocity (V\*) with relative tracer size (D\*) for all individual tracers and for the respective grain sizes classes. The solid line is the best-fit line for the V\* - D\* relationship in the six grain size classes traced. (b) Relationship between mean virtual velocity (Vvm) and excess stream power (ωp -ωc) measured in the intra-survey periods. Blue diamonds are the Rio Cordon data during the period 2012-2018 and the solid line is the best-fit line. This was compared to the relationships observed in Lainbach Stream (Gintz et al., 1996), Riffle pool channels (Hassan et al., 1992), Ardenne rivers (Houbrechts et al., 2015) and Spruce Creek (Lamarre and Roy, 2008).

**Table 1** Main characteristics of flood events recorded by the Rio Cordon monitoring station during the study period (2012-2018). *Qp\_flood* is the peak of water discharge recorded during the flood, *RI* is the recurrence interval, *BL* the bedload volume transported to the monitoring station, *D50*and *Dmax*are the 50th percentile and largest particles of the bedload material, respectively.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | *Qp\_flood* | *RI* | *BL* | *D50* | *Dmax* |
|  | (m3 s-1) | (years) | (m3) | (mm) | (mm) |
| 11 November 2012 | 2.10 | 1.7 | 14.2 | 38 | 300 |
| 17 May 2013 | 1.98 | 1.5 | 2.2 | 44 | 340 |
| 9 June 2014 | 2.06 | 1.7 | 65.6 | 41 | 230 |
| 5 November 2014 | 2.06 | 1.7 | 2.7 | 38 | 220 |
| 28 May 2016 | 1.09 | 1.0 | 0.5 | 35 | 96 |
| 24 May 2018 | 1.67 | 1.3 | 3.6 | 36 | 180 |

**Table 2** Summary of the hydrological forcing conditions registered during the intra-survey periods (P1 – P14) and effect on tracers mobility: *Dates* identify the extent of the period analyzed; *Dominant regime* describes the typology of prevailing flow (R = rainfall-driven, S = snowmelt-induced, M = mixed nature); *Qp*, *Qmean* and *Qmed*are peak, mean and median of discharge recorded, respectively; *qp* is the peak of unit discharge; *ωp* – *ωc* the excess specific stream power; *tover* is the over-threshold time (*Q* ≥ 0.44 m3 s-1); *ER* the effective runoff volume; *Rr* is the recovery rate about the tracers; *Mobilized classes* reports the fraction of tracer size classes mobilized; *Lm* and *Vvm* are the mean transport distance and mean virtual velocity estimated considering all tracers (moved or not), respectively.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | *Dates* | *Dominant regime* | *Qp* | *Qmean* | *Qmed* | *qp* | *ωp* -*ωc* | *tover* | *ER* | *Rr* | *Mobilized classes* | *Lm* | *Vvm* |
|  | (m3 s-1) | (m3 s-1) | (m3 s-1) | (m2 s-1) | (W m-2) | (h) | (103 m3) | (%) | (mm) | (m) | (m h-1) |
| P1 | 07/05/12 – 22/11/12 | R | 2.10 | 0.24 | 0.19 | 0.508 | 469.0 | 481 | 461.6 | 60 | 45.3 – 256.0 | 81.56 | 0.438 |
| P2 | 23/11/12 – 25/07/13 | M | 1.98 | 0.43 | 0.33 | 0.498 | 456.3 | 1391 | 2107.6 | 59 | 45.3 – 181.0 | 5.99 | 0.006 |
| P3 | 26/07/13 – 14/10/13 | R | 0.72 | 0.13 | 0.11 | 0.206 | 94.7 | 8 | 7.94 | 47 | 45.3 – 90.5 | 0.41 | 0.055 |
| P4 | 15/10/13 – 15/05/14 | S | 1.00 | 0.17 | 0.09 | 0.277 | 183.2 | 263 | 256.8 | 54 | 45.3 – 128.0 | 0.54 | 0.004 |
| P5 | 16/05/14 – 01/07/14 | M | 2.06 | 0.88 | 0.87 | 0.502 | 461.5 | 722 | 1172.7 | 63 | 45.3 – 256.0 | 77.18 | 0.274 |
| P6 | 02/07/14 – 25/08/14 | R | 0.85 | 0.40 | 0.37 | 0.235 | 131.3 | 363 | 96.6 | 64 | 45.3 – 128.0 | 0.17 | 0.030 |
| P7 | 26/08/14 – 29/10/14 | R | 0.44 | 0.18 | 0.16 | 0.129 | - | 6 | - | 61 | 45.3 – 64.0 | 0.02 | 0.007 |
| P8 | 30/10/14 – 24/11/14 | R | 2.06 | 0.57 | 0.10 | 0.502 | 461.5 | 140 | 369.3 | 58 | 45.3 – 256.0 | 59.30 | 0.723 |
| P9 | 25/11/14 – 18/05/15 | S | 0.83 | 0.18 | 0.10 | 0.234 | 129.6 | 265 | 146.6 | 59 | 45.3 – 128.0 | 0.06 | 0.008 |
| P10 | 19/05/15 – 26/08/15 | M | 0.68 | 0.22 | 0.18 | 0.196 | 83.1 | 227 | 54.5 | 63 | 45.3 – 64.0 | 0.02 | 0.001 |
| P11 | 27/08/15 – 06/09/16 | S | 1.09 | 0.31 | 0.23 | 0.301 | 212.3 | 1060 | 877.7 | 61 | 45.3 – 181.0 | 0.19 | 0.005 |
| P12 | 07/09/16 – 27/09/17 | M | 1.01 | 0.16 | 0.13 | 0.280 | 186.3 | 236 | 113.9 | 51 | 45.3 – 128.0 | 0.11 | 0.004 |
| P13 | 28/09/17 – 28/06/18 | S | 1.67 | 0.38 | 0.24 | 0.443 | 388.0 | 1490 | 1493.6 | 52 | 45.3 – 181.0 | 2.72 | 0.007 |
| P14 | 29/06/18 – 04/10/18 | R | 1.16 | 0.35 | 0.29 | 0.319 | 234.4 | 675 | 458.6 | 63 | 45.3 – 181.0 | 0.20 | 0.029 |

**Table 3**Power laws (*y = αxβ*) fitted to describe *Lm* measured in the intra-survey periods. In bold the significant p-values.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | *α* | *β* | *R2* | *p-value* |
| *Qp* | 0.37 | 5.53 | 0.83 | **0.001** |
| *Qmean* | 59.02 | 3.46 | 0.41 | **0.013** |
| *Qmed* | 8.74 | 1.51 | 0.10 | 0.265 |
| *qp* | 1159.10 | 6.19 | 0.80 | **0.001** |
| *ωp* -*ωc* | 5.43E-10 | 3.99 | 0.77 | **0.001** |
| *tover* | 0.02 | 0.64 | 0.13 | 0.200 |
| *ER* | 4.56E-03 | 0.97 | 0.27 | 0.067 |

**Table 4** Power laws (*y = αxβ*) fitted to describe *Vvm* measured in the intra-survey periods. In bold the significant p-values.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | *α* | *β* | *R2* | *p-value* |
| *Qp* | 0.01 | 2.57 | 0.33 | **0.032** |
| *Qmean* | 0.18 | 1.88 | 0.21 | 0.093 |
| *Qmed* | 0.05 | 0.67 | 0.03 | 0.512 |
| *qp* | 0.48 | 2.81 | 0.30 | **0.043** |
| *ωp* -*ωc* | 2.09E-07 | 2.10 | 0.34 | **0.037** |
| *tover* | 0.02 | -0.04 | 0.01 | 0.898 |
| *ER* | 5.20E-03 | 0.22 | 0.02 | 0.623 |

**Table 5** Summary of main characteristics examined and results achieved in this work, and in other similar bedload mobility investigations: w is the channel width; s is the channel slope, SM describes the prevalent stream morphology in step-pool (SP), riffle-pool (RP) and plane bed (PB); D50 is the median diameter of surface grain size distribution; Tracers and n describe typology and number of tracers used, respectively; Dtracers is the range of tracer diameters; T represents the extent of the study period; Rr the recovery rate; Counted describes the approach used to determine the transport distance, i.e., by considering all tracers (moved and not) or if the moved only; L and Vv are the transport distance and the virtual velocity observed, respectively.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Study site* | *Reference* | *w* | *s* | *SM* | *D50* | *Tracers* | *n* | *Dtracers* | *T* | *Rr* | *Counted* | *L* | *Vv* |
| (m) | (m m-1) |  | (mm) |  |  | (mm) | (years) | (%) |  | (m) | (m h-1) |
| Rio  Cordon | This work | 5.7 | 0.125 | SP | 114 | RFID | 250 | 33 - 210 | 7 | 47 - 64 | Moved and not | 0.02 – 81.56 | 0.001 - 0.723 |
| Ardenne  rivers | Houbrechts et al.  (2015) | 10.5 | 0.002 - 0.009 | RP | 36 - 113 | RFID | > 1000 | - | 7 | 62 - 97 | Moved and not | 1 - 271 | 1.9 – 126.4a |
| Bouinenc Torrent | Liébault et al.  (2012) | 24.0 | 0.016 | RP | 20 | RFID | 451 | 23 - 520 | 3 | 89 - 45 | Moved and not | 75 - 336 | 5 - 150 |
| Carnation  Creek | Haschenburger and  Church  (1998) | 13.0 | 0.005 - 0.010 | RP | 47 | Magnetic | 1000 | 16 - 180 | 2 | 9 - 94 | Moved only | 26 - 129 | 0.78 - 5.80 |
| Erlenbach Stream | Schneider et al.  (2014) | 3.5 | 0.150 | SP | 64 | RFID  Magnetic | > 1000 | 28 - 160 | 7 | 1 - 77 | Moved only | 7 - 161 | - |
| Halfmoon  Creek | Bradley and Tucker  (2012) | 10.0 | 0.01 | RP | 55 | RFID | 893 | 40 - 90 | 4 | 93 - 98 | Moved and not | 2 - 114 | - |
| Lainbach Stream | Gintz et al.  (1996) | 10.0 | 0.02 | SP | 120 | Iron  Magnetic | > 1000 | 30 - 170 | 4 | 23 - 100 | Moved and not | 1 - 317 | 2 - 47 |
| Nicea  River | Vázquez-Tarrío and Menéndez-Duarte  (2014) | 14.0 | 0.007 - 0.010 | RP | 56 - 88 | Painted  Magnetic | > 1000 | 16 - 256 | 3 | 0 - 100 | Moved only | 2 - 66 | - |
| Rio  Cordon | Lenzi (2004) | 5.3 | 0.136 | SP | 127 | Painted  Active radio | 860 | 32 - 512 | 6 | 65 | Moved and not | 1 - 142 | - |
| Spruce  Creek | Lamarre and Roy (2008) | 6.0 | 0.140 | SP | 160 | RFID | 196 | 25 - 250 | 4 | 57 - 92 | Moved only | 1.5 – 8.3 | 0.02 – 0.09 |
| Strimm  Creek | Dell'Agnese et al.  (2015) | 3.7 | 0.008 - 0.150 | SP/PB | 62 - 76 | RFID | 490 | 23 - 229 | 3 | 54 - 100 | Moved only | 0.3 - 200.0b | 0.001 - 4.40b/c |
| Wood Brook Creek | Dudley  (2007) | 2.2 | 0.03 | SP | 41 - 241 | Magnetic | 300 | 12 - 64 | 1 | 90 | Moved and not | 0.1 - 2.5 | - |

a Vv expressed in m yr-1

b median values

c *Vv* expressed in cm min-1