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Bedload transport in a steep alpine stream: Assessment of sediment mobility and virtual velocity using the bedload tracking

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Abstract. The bedload transport is challenging to analyze in field, consequently, several assumptions about it were made basing on laboratory researches or on short-term field studies. During the last decades several monitoring methods were developed to assess the bedload transport in the fluvial systems. The aim of this work is to investigate the transport of the coarse sediment material in a steep alpine stream, using the bedload tracking. The Rio Cordon is a typical alpine channel, located in the northeast of Italy. It is characterized by a rough streambed with a prevalent boulder-cascade and step pool morphology. Since 2011, 250 clasts equipped with Passive Integrated Transponders (PIT) were installed in the main channel, to analyze their mobility along a reach 320 m long. From November 2012 to August 2015, the transport induced by a range of hydraulic forcing between 0.44 m^3 s^{-1} and 2.10 m^3 s^{-1} was assessed by 10 PIT-surveys. First, the mobility expressed by the tracers was analyzed, observing marked differences in terms of travel distance. Then, the average recovery rate achieved during the tracer inventories (Rr > 70%) permitted to define the threshold discharge for each grain size class analyzed and, then, to assess the virtual velocity experienced by the tracers.

1. Introduction

Notoriously, the bedload transport is challenging to analyze in field and, thus, several assumptions about this topic were made basing on laboratory researches or on short-term field studies. Generally, these approaches may tend to overestimate the bedload magnitude, particularly when used to assess the low magnitude/high frequency flood events [1, 2]. This boundary contrasts with the importance that bedload transport has in the fluvial systems, and especially in the mountain channels where it can strongly influence the morphological setting, ecological status, channel stability and sediment fluxes [3, 4, 5]. In light of this, during the last decades several monitoring methods were developed to assess the bedload

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transport in the fluvial systems. Generally, the bedload is monitored using portable or permanent sediment traps and acoustic sensors, which assess the sediment fluxes along fixed cross-sections [6, 7, 8]. Since the 90's, the introduction of the tracking method help to better comprehend the dynamics of coarse sediment mobility [9, 10]. Started from clasts simply colored, in the last decade the tracking method has largely used the RFID technology and, specifically, the Passive Integrated Transponders (PIT). Once equipped with PIT, the clast chosen as tracers can be identified by a specific ID and, thus, can be periodically localized along the channel network [11, 12]. Specifically, the PITs are detectable by mobile or fixed antennas, which permit to identify the PIT even if buried and, then, to investigate the bedload dynamics with no disturbance to the streambed organization [13].

In steep mountain streams, the PIT-tracers can enable to better comprehend the relation between the hydraulic forcing conditions and sediment mobility [14, 15], permitting even to investigate the effect of different geomorphic conditions on the sediment transfer dynamics [16]. Due to the main features of the mountain streams, i.e. a highly heterogeneous streambed material and a wide range of hydraulic forcing conditions, the tracking method is particularly suitable both to identify the entrainment threshold of the different grain size fractions [17], and, being based on the monitoring of single particles, to assess the virtual velocity expressed by the clasts during bedload event [16]. Particularly, the virtual velocity of bedload propagation can be calculate when results about the distance travelled by the tracers in conjunction with the time interval of motion are available. The PITs monitoring can be realized by continuous measurements (e.g. stationary antenna) or by periodically surveys (e.g. mobile antenna), in the latter case the virtual velocity estimated may be lower than the actual velocity experienced by the bedload, because accounted both periods of rest and transport [10]. In mountain streams, only few studies investigated the virtual velocity expressed by the bedload material and most of these analyzed the sediment dynamics over the short-term [10, 16, 18], while only few authors dealt with the bedload propagation over long-time scales [13]. In this sense, the analyses performed over long-term (i.e. > 5 years) stressed that the virtual velocity can exhibits a significant decrease over time due to the deposition of tracers in inactive part of the streambed and to the increase of buried ones [19].

The aim of this work is to investigate the transport dynamics of the coarse sediment material in a steep alpine stream, using the bedload tracking method. Firstly, the mobility expressed by 250 Pit-tags over the period 2012-2015 was examined. Secondly, the threshold discharges for the different grain size classes tracked were assessed and, then, the virtual velocities experienced by the tracers in the inter-survey periods were calculated.

2. Material and methods

2.1. Study area

The study area selected for the monitoring of bedload by the tracking method is the Rio Cordon (Dolomites, Eastern Italian Alps). The Rio Cordon basin is a typical alpine basin, extended 5 km^2. The catchment exhibits alpine climatic conditions with mean annual rainfall equal to 1150 mm. Overall, the basin area is principally covered by Alpine grassland with a wide presence of sediment source areas [20]. The Rio Cordon stream flows on a rough channel-bed, which exhibits a prevalent boulder-cascade and step-pool configuration. The average slope of the main channel is equal to 17%, that decreases to 13% in the downstream part. The streambed is strongly armoured with a surface streambed material characterized by $D_{16}/D_{50}/D_{84}/D_{90}$ of grain size distribution equal to 29/114/358/455 mm [2].

2.2. Hydrological data

In the Rio Cordon basin, a permanent monitoring station is active since 1986. It was realized at the outlet of the catchment (1763 m a.s.l.) permitting the continuous measurement of water discharge (Q) and sediment fluxes (suspended load and bedload). Particularly, the water discharge is hourly measured in three different points of the station, by two water level gauges and a sharp-crested weir. In case of flood event (i.e. $Q > 1.00$ m^3 s^{-1}), the sampling interval change to 5 min. Thanks to data recorded by the monitoring station and field observations, the bankfull discharge was estimated by [21] equal to 2.30 m^3 s^{-1}. Currently, the monitoring station is managed by the ARPA Veneto, Regional Department for Land Safety. A detailed description of the Rio Cordon monitoring station (structure, instruments) can be found in [2, 22].

2.3. Tracing method

To investigate the sediment mobility, 250 tracers equipped with PIT-tags were progressively installed in the Rio Cordon stream. Using PIT 23 mm long, a range of *b-axis* equal to 33-190 mm was tracked. In terms of grain size, this fraction corresponds to $D_{25} < D < D_{70}$ of the surface streambed material, tracing the grain size classes between 45.3 to 256.0 mm. From May 2011 to May 2012, the tracers were progressively seeded along three cross sections located approximately 320 m upstream of the permanent monitoring station (i.e. basin outlet). The study reach thus determined has an average slope of 13% and a sequence of boulder-cascade and riffle-step-pool configurations. The reach was organized into 23 straight stretches, using the cross sections that delimit them as reference points to measure the distance travelled by the tracers [15]. The monitoring of the tracer's mobility started in May 2012. The PIT surveys were performed periodically and after each flood event recorded by the permanent monitoring station (Fig. 1). A RFID mobile antenna (Aquartis Accueil®) was used to detect the PIT-tag positions, while a high-precision laser rangefinder (LaserTech®) was employed to measure the travel distance along the thalweg. Normally, the field surveys required 1-2 days per PIT inventory. Due to difficult in-channel operations (rough streambed) and to the instrument detection range [23], the uncertainty associated to the tracer positioning was considered equal to 1 m. Hence, the displacements lower than this threshold was not considered for the analysis.

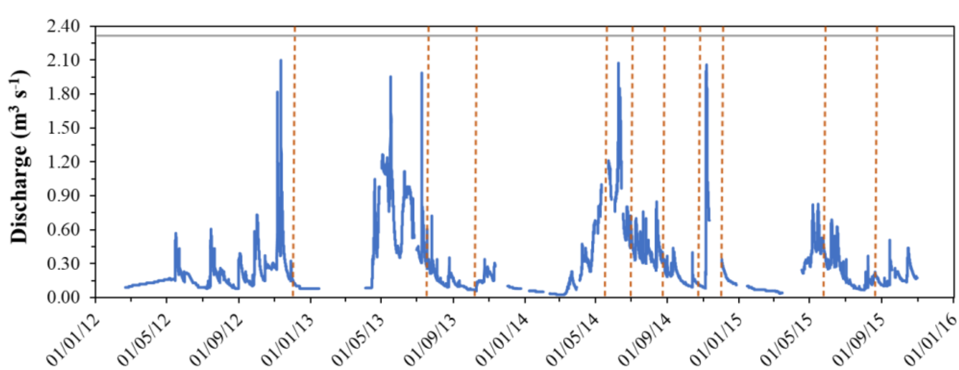

Fig. 1. Water discharge recorded by the Rio Cordon monitoring station in the period 2012-2015. The dashed vertical lines show the PIT surveys, while the grey horizontal line is the bankfull discharge.

2.4. Flow competence and virtual velocity evaluation

Basing on the results obtained by the PIT surveys, the threshold discharges (Q_{ci}) for the motion of the grain size classes traced were identified as the minimum discharge value between the maximum Q that not trigger motion in the i class and the minimum Q which caused transport in the same class. Such approach is derived by the competence method [24, 25] and is frequently used in steep alpine streams [16]. Once determine the Q_{ci}, for each grain size classes the over-threshold flow duration in the inter-survey period was calculated [13]. Then, the virtual velocity (Vv) expressed by each tracer during the periods investigated was determined as ratio between the travel distance and the competent flow duration, i.e. the over-threshold flow duration of the corresponding grain size class.

3. RESULTS

Overall, 10 PIT surveys were realized between May 2012 to August 2015 (Table 1). Particularly, the study period started on May 7, 2012, when the PIT-installation phase has been completed. In terms of duration, the inter-survey periods delimited by the 10 PIT inventories range between 26 to 245 days, with, on average, a survey every 120 days. The range of Q_{peak} investigated varies by one order of magnitude, i.e. between 0.44 to 2.10 m^3 s^{-1}, while the recovery rates were constantly $\geq$ 65% with an average equal to 73.5%. Interestingly, the mean travel distance experienced by the tracers (Li) spans two order of magnitude, from Li = 1.08 m observed as response of the period 10 to Li = 117.03 m triggered during the period 5 (Table 1).

Table 1. Results of the PIT surveys: Period identify the inter-survey time interval, the date corresponding to the end of the period (e.g. 22/11/12) corresponds to the PIT survey; Q_{peak} is the peak of discharge recorded during the inter-survey period; Rr is the recovery rate about the tracers, Li is the mean travel distance, Mobilized Classes show the range of grain size classes mobilized.

ID	Period	Q_{peak} (m^3 s^{-1})	Rr (%)	Li (m)	Mobilized Classes (mm)
1	07/05/12 - 22/11/12	2.10	78.0	98.80	45.3 - 128.0
2	23/11/12 - 25/07/13	1.98	78.0	13.71	45.3 - 181.0
3	26/07/13 - 14/10/13	0.72	65.0	2.75	45.3 - 128.0
4	15/10/13 - 15/05/14	1.00	86.0	2.48	45.3 - 181.0
5	16/05/14 - 01/07/14	2.06	77.0	117.03	45.3 - 256.0
6	02/07/14 - 25/08/14	0.85	75.0	1.65	45.3 - 181.0
7	26/08/14 - 29/10/14	0.44	73.0	1.23	45.3 - 64.0
8	30/10/14 - 24/11/14	2.06	70.0	95.18	45.3 - 256.0
9	25/11/14 - 18/05/15	0.83	65.0	1.27	45.3 - 128.0
10	19/05/15 - 26/08/15	0.68	68.0	1.08	45.3 - 90.5

Precisely, the first period analyzed (period 1, 199 days) began on May 2012 and ended with the first PIT inventory (22 November 2012). During this time interval, the peak of discharge (Q_{peak}) was 2.10 m^3 s^{-1}, that has been recorded on 11 November 2012 as consequence of a rainfall-driven flood event. Despite the extent of the inter-survey period and the high hydraulic forcing, a recovery rate equal to 78% was achieved during the PIT inventory (Table 1). In terms of sediment mobility, the hydrological conditions occurred in the period 1 led, on one hand, to a mean travel distance experienced by the tracers (*Li*) equal to 98.80 m, and on other hand, to the motion of the grain size classes up to 128.0 mm.

During the study period, the highest *Li* (117.03 m) was observed as response of the period 5. Despite the short duration of the inter-survey period (47 days), the PIT inventory detected the motion of all grain size tracked (Table 1). In this case, Q_{peak} reached 2.06 m^3 s^{-1} during a rain-on-snow event occurred in early June 2014. On the other hand, the lowest *Li* (1.08 m) was recorded in the most recent PIT inventory. In this sense, the period 10 (100 days) shown the effect induced by hydraulic forcing of the late snowmelt-early summer 2015 on the tracer mobility. Notwithstanding the mixed climatic nature of the period, the water discharge has been constantly < 0.70 m^3 s^{-1} with a Q_{peak} = 0.68 m^3 s^{-1}, and the motion of the only grain size classes up to 90.5 mm. The lowest Q_{peak} (0.44 m^3 s^{-1}) was recorded in the period 7, triggering *Li* equal to 1.23 m. As consequence of this period, merely the classes 45.3 and 64.0 mm were mobilized.

In addition to the sediment mobility, the results achieved by the PIT surveys permitted, thus, to investigate the threshold discharges (Q_{ci}) for the motion of the grain size classes traced. Only two periods (5, 8) caused the transport of all class investigated (45.3 - 256.0 mm) and, interestingly, in both cases Q_{peak} was 2.06 m^3 s^{-1}. Specifically, the results seem to suggest that the finer grain sizes, i.e. the fraction between 45.3 to 64.0 mm, can be mobilized by $Q \geq 0.44$ m^3 s^{-1}, while the grain size classes 90.5, 128.0, 181.0 and 256.0 mm were transported by $Q > 0.44$ m^3 s^{-1}, $Q > 0.68$ m^3 s^{-1}, $Q > 0.83$ m^3 s^{-1} and $Q > 1.98$ m^3 s^{-1}, respectively. Over the entire study period, the threshold discharge for the grain size classes 45.3-64.0 mm was exceeded for the 16.7 % of the time, while for the classes 90.5, 128.0, 181.0 and 256.0 mm the exceedance duration is 15.7 %, 8.6 %, 6.0% and 0.1 %, respectively.

The identification of threshold discharges enabled to identify, in each inter-survey period, the competent flow duration for each grain size classes. In turn, the definition of the over-threshold flow duration allowed the virtual velocity expressed by the tracers to be calculated. The maximum propagation velocity for a single tracer was observed in period 5, with a PIT-tag that expressed a Vv = 18.3 cm min^{-1}. In terms of median virtual velocities, the values vary by two orders of magnitude between the various inter-survey periods (Fig. 2), by ranging from 0.008 (periods 6 and 10) to 0.948 cm min^{-1} (period 8).

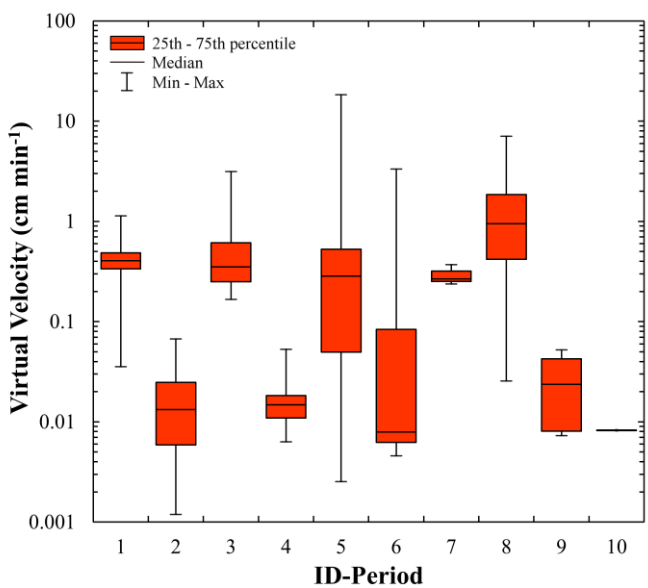

Fig. 2. Box plots of the virtual velocities expressed by the tracers during the inter-survey periods.

4. DISCUSSION AND CONCLUSION

In the Rio Cordon, the bedload monitoring program undertaken using the tracking approach has permitted to investigate, during the period 2012-2015, the sediment mobility and the virtual velocity expressed by 250 clasts. The range of Q_{peak} analyzed varies between 0.44 to 2.10 m^3 s^{-1}, i.e. under- and near-bankfull flow conditions. Specifically, the PIT-surveys enabled to examine both short periods (< 30 days) affected by flood events as well as longer time intervals influenced by long snowmelt-driven flows. In the 10 PIT-surveys performed, an average recovery rates (*Rr*) equal to 73.5 % was reached. Such ratio of tracers recovered is in line with the results achieved by similar works focused on the bedload tracking [11 - 14], permitting to accurately analyze the sediment mobility. The mean travel distance of the tracers (*Li*) spans two order of magnitude (1.08 - 117.03 m) suggesting that, despite the ordinary hydrological conditions occurred, a large fraction of streambed material can be mobilized for long distances (> 100 m). These results appear in line with the travel distance observed in the Strimm Creek (eastern Italian alps), which features setting conditions comparable to the Rio Cordon [16]. In this study site, the authors observed maximum displacements between 1.20 and 959.00 m as response of Q_{peak} 0.32 -1.80 m^3 s^{-1}. Notably, in the Rio Cordon the higher *Li* were observed in the period affected by flood events, i.e. period 1, 5, 8.

Thanks to the 10 PIT-surveys, the grain size classes tracked (45.3 - 256.0 mm) were analysed in terms of threshold discharge. Interestingly, the motion of the finer fraction of tracers (45.3 – 64.0 mm) started with $Q \geq 0.44$ m^3 s^{-1}, while the mobilization of the coarser tracer fraction (256.0 mm) was observed only in the periods 5 and 8, i.e. for $Q > 1.98$ m^3 s^{-1}. These thresholds appear slightly lower than the critical discharges previously determined in the Rio Cordon [25, 26]. Basing on the displacement of marked (coloured) clasts during the period 1993 - 1998, the authors demonstrated that $D = 50$ mm was mobilized by $Q = 0.50$ m^3 s^{-1}, while $Q = 2.90$ m^3 s^{-1} was able to entrain $D = 215$ mm. This slight dissimilarity might be explained, on one hand, by the different tracers used (coloured clasts vs. PIT-tags) and, on the other hand, by the different streambed organization. In the period 2013 - 2015, the sediment mobility was analyzed while the Rio Cordon streambed showed stable bedforms with a strongly armoured layer. Differently, in the period 1993 - 1998, the study site suffered strong alterations in terms of channel bed configuration, due to the occurrence of an exceptional event [2].

The median virtual velocities observed in the Rio Cordon vary by two orders of magnitude, ranging from 0.008 to 0.948 cm min^{-1}. Similar results were observed in two basins located in the eastern Italian alps, i.e. the Strimm Creek and Saldur River [16, 18]. Particularly, in the former study site $Vv = 0.001$ - 4.000 cm min^{-1} were detected as response of Q between 0.32 and 1.80 m^3 s^{-1}, while in the latter $Q = 1.40$ - 14.30 m^3 s^{-1} triggered Vv of single tracers between 0.00001 and 35 m min^{-1}. On the other hand, the virtual velocities noted in the Rio Cordon are lower than those assessed in the Carnation Creek (British Columbia) [10]. Here, the authors detected velocity propagation equal to 0.78 - 5.80 m h^{-1} (0.005 - 0.735 in the Rio Cordon). The use of magnetically tagged stones in the Carnation Creek and, in particular, the higher hydraulic forcing condition monitored, i.e. $17 < Q < 36$ m^3 s^{-1}, might explain the different propagation velocities. Differently than *Li*, in the Rio Cordon the virtual velocities experienced by the tracers during the inter-survey periods seem to be not related to Q_{peak}. In fact, in the three periods with $Q_{peak} > 2.00$ m^3 s^{-1} (period 1, 5 and 8) the median Vv were 0.404, 0.284 and 0.948 cm min^{-1}, respectively. This result stress that further analyses are required to better comprehend the relation between the virtual velocities and the flood event features (e.g. effective runoff volume and over-threshold flow duration).

The results achieved by this study highlighted the complex dynamics that can characterizes the mobility of the coarse material in an alpine stream. In this sense, the bedload tracking appeared as a useful method to investigate the sediment dynamics (bedload) even along several years (≥ 2 years). Particularly, the use of the tracers is not bound by the definition of fixed cross sections from which monitor the sediment transport, but can enable to analyze the mobility of single particles along their travel. Also, if coupled to the definition of active-layer depth and -channel width, the tracing method can permit even to evaluate the bedload yield due to single flood events. In light of this, the bedload tracking appears as a useful approach for many applications as river management and hazard assessment, as permits to better comprehend different aspects of bedload transport.

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