Rio Cordon instrumented basin: monitoring and investigation of June 2014 bedload event

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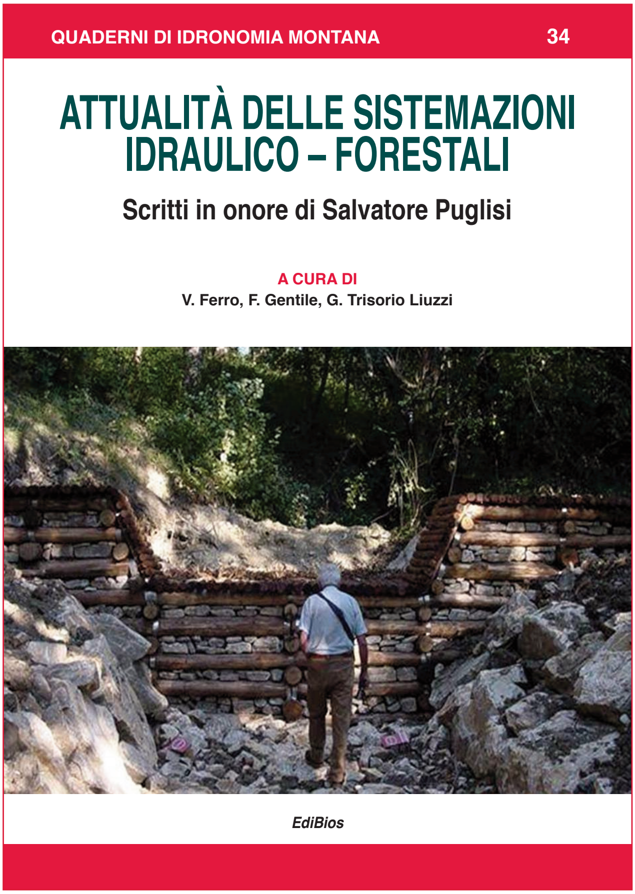

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RIO CORDON INSTRUMENTED BASIN: MONITORING AND INVESTIGATION OF JUNE 2014 BEDLOAD EVENT

Il bacino attrezzato del Rio Cordon: monitoraggio ed analisi dell'evento di trasporto solido di fondo avvenuto nel Giugno 2014

R. Rainato, L. Picco*, M.A. Lenzi**

Summary

In mountain environments, the analysis and quantification of bedload process are of fundamental importance for hazard assessment, understanding the morphodynamics of higher order channels, planning and designing reservoir sedimentation. The importance of bedload knowledge contrasts with the fact that it is difficult to monitor, especially in small, steep mountain basins, due to its impulsive nature. Consequently, field bedload data are relatively scarce, and monitoring programs maintained continuously over long-term periods are particularly rare. This work aims to investigate the bedload event occurred on June 9, 2014 in the Rio Cordon instrumented basin (Eastern Italian Alps). The Rio Cordon is a high gradient channel characterized by step-pool and riffle-pool morphology, and by a mean slope equal to 13%. The basin extends for 5 km^2 and exhibits a prevalent nivo-pluvial runoff regime. Since 1986, the catchment is equipped with a monitoring station, that continuously records water discharge, bedload and suspended load (at 1 hr intervals, and 5 min intervals during floods). Currently, the structure is managed by ARPA Veneto – Regional Department for Land Safety. The data recorded by the station during the 2014-flood allowed the hydrological features of the event to be characterized. Moreover, multiple post-flood surveys were carried out to determine amount and grain size characteristics of the coarse material transported, as well as to detect its source area. Bedload occurred during a mixed snowmelt-rainfall event lasted more than 14 hours, peaking to 2.06 $m^3 s^{-1}$ (RI = 1.7 years). Overall, 65.3 m^3 of coarse material were mobilized. In terms of bedload magnitude, the flood event appears as the sixth most important recorded event. To assess the grain size characteristics of bedload material, 262 transported clasts were measured. The largest particle mobilized is characterized by a *b-axis* equal to 230 mm, while D_{50} is 41 mm. In terms of particle-size, the coarse material appears comparable with that transported by the most recent bedload events, especially if supplied by hillslope processes (i.e. November 2012). Field evidences (i.e traces of moved loam) suggested that a debris flow channel located in the median part of the basin was the main source area. The results suggest that the Rio Cordon creek, despite a channel-bed strongly armoured, may transport large amounts of sediment also during no extraordinary flood events. In this

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sense, the morphological setting of the basin and the presence of many areas potentially unstable may trigger a significant sediment supply.

Sommario

In ambiente montano, l'analisi e la quantificazione dei processi di traposto solido di fondo sono di fondamentale importanza per la valutazione del pericolo, comprendere le condizioni morfo-dinamiche dei torrenti montani, pianificare e progettare gli invasi di sedimentazione. L'importanza del trasporto di fondo contrasta con la difficoltà nel monitorarlo, in particolare nei piccoli bacini montani caratterizzati da elevate pendenze, a causa della sua natura impulsiva. Di conseguenza, dati di campo riguardanti il trasporto di fondo sono relativamente scarsi, ed i programmi di monitoraggio mantenuti continuativamente nel lungo periodo sono particolarmente rari. Il lavoro qui presentato ha lo scopo di indagare l'evento di trasporto di fondo verificatosi il 9 Giugno 2014 nel bacino attrezzato del Rio Cordon (Dolomiti Venete). Il Rio Cordon è un torrente montano caratterizzato da una morfologia *step-pool* e *riffle-pool*, con una pendenza media del 13%. Il bacino ha un estensione pari a 5 km^2 e un regime dei deflussi dominato da scioglimento nivale e precipitazioni piovose. Dal 1986, il bacino è stato attrezzato con una stazione di monitoraggio permanente, la quale registra in continuo la portata liquida così come il trasporto solido di fondo ed in sospensione (intervalli di 1h, ogni 5 min durante eventi di piena). Attualmente, la struttura è gestita dall' ARPA Veneto – Dipartimento Regionale per la Sicurezza del Territorio. I dati prodotti dalla stazione di monitoraggio durante la piena del Giugno 2014 hanno permesso di determinare le caratteristiche idrologiche dell'evento. Inoltre, diversi rilievi di campo post-piena sono stati eseguiti al fine di determinare la quantità e le caratteristiche granulometriche del materiale trasportato, così come individuarne l'area sorgente. Il trasporto di fondo si è verificato durante un evento di piena alimentato sia da scioglimento nivale che da deflussi da precipitazione. La fase di piena è durata per oltre 14 ore, con una portata al picco pari a 2.06 $m^3 s^{-1}$ (RI = 1.7 anni). Complessivamente, 65.3 m^3 di materiale grossolano sono state trasportate alla stazione. In termini di magnitudo di trasporto di fondo, l'evento del 9 Giugno 2014 appare come il sesto maggior evento registrato dalla stazione. Al fine di valutare le caratteristiche granulometriche del materiale trasportato, 262 clasti sono stati misurati. Il maggior diametro mobilitato è stato pari a 230 mm, mentre il D_{50} è risultato uguale a 41 mm. In termini di granulometria, il sedimento trasportato risulta comparabile con il materiale mobilitato durante i più recenti eventi di trasporto, soprattutto se alimentati da fenomeni di versante (i.e. Novembre 2012). Evidenze di campo (i.e. tracce di terreno smosso) hanno messo in risalto come un canale da colata situato nella parte mediana del bacino sia stato la principale area sorgente. I risultati suggeriscono come il torrente Rio Cordon, nonostante un forte corazzamento dell'alveo, possa trasportare grandi quantità di materiale anche durante eventi non eccezionali. In questo senso, la configurazione morfologica del bacino e la presenza di numerose aree potenzialmente instabili possono innescare un significativo apporto solido.

1. Introduction

The transport of coarse material, i.e. bedload, plays a key role in the fluvial systems. In terms of fluvial morphology, such phenomenon influences both bedforms and channel configuration (Baewert and Morche, 2014), triggering also changes in the ecosystems, in particular on spawning habitats of fish species, macro- and micro-invertebrates (Wohl, 2015). Due to the high energy conditions in which the bedload takes place, its analysis appears highly useful also for the hazards assessment and infrastructure design. Therefore, the understanding and analysis of bedload is an essential aspect for a wide range of applications. Notwithstanding such role, many aspects of bedload phenomenon still remain to outline and clarify, especially if referred to the high gradient streams. In mountain environment, the main features of bedload are even more stressed (e.g. high gradient, availability of coarse material, impulsive nature of fluxes), consequently the bedload monitoring on the one hand is highly challenging, but on the other hand may allow to obtain very valuable results. During the last decades, several direct and indirect methods to monitoring the bedload were developed. The bedload traps represent a direct method because they permit to gather the amount of material transported in a unit of time, allowing to investigate the transport rate and grain size characteristics of material mobilized (Bunte et al., 2008). The traps can be employed both as portable device (i.e. Bunte and Helley Smith sampler) or installed on permanent monitoring stations, thus enabling long-term investigations. On the other hand, the bedload tracing and geophones based on acoustic or seismic technology are the main indirect methods used to monitor the transport of coarse material in the mountain streams. Particularly, in the last two decades several methods to track the bedload were developed, and once applied in field allowed valuable data about incipient motion and sediment mobility conditions to be achieved (Lenzi et al., 2006a; Olinde and Johnson, 2015). The technological innovation has enabled to continuously improve the amount and quality of data recordable by geophones, shedding light on the transport rate and timing that characterize the bedload events (Rickenmann et al., 2012; Mao et al., 2015). As regards the mountain streams, an overall lack of field bedload data can be noted and, furthermore, few monitoring programs are maintained continuously active over long-term. In this sense, long time scale data series are fundamental to comprehend the sediment dynamics both on short- and long-term (Turowski et al., 2010). Analyze the features of single event enables to investigate the hydrological and sedimentological magnitude triggered by the floods (Lenzi et al., 2004), while precious results concerning inter-annual trends of sediment yield, partitioning and sediment supply may be achieved if such investigation is performed over long time scale (Rainato et al., 2016). In this work, the bedload event occurred on June, 9 2014 in the Rio Cordon basin is examined. Since 1986, the Rio Cordon catchment is equipped with a permanent monitoring station designed to the continuous measurement of water discharge and sediment fluxes. The devices installed into the instrumented basin allowed to analyse the rainfall, discharge, bedload and grain size characteristics of material mobilized during the June 2014 event. Additionally, the source area has been detected and mapped. The achieved results enabled to analyze in detail the sediment dynamics occurred during the June 2014 bedload event, updating the Rio Cordon-dataset, and to compare such results with more recent dynamics observed in the study site.

2. **Material and methods**

2.1 Study area

The Rio Cordon basin (Fig. 1) is located in the eastern Italian Alps (Dolomites). The basin drains a surface of 5 km^2, and elevations range from 1763 to 2763 m a.s.l. The basin is characterized by typical Alpine climatic conditions with an average annual precipitation of 1150 mm that occurs mainly as snowfall between November and April and as storms in the summer season. The runoff therefore exhibits a nivo-pluvial regime dominated by snowmelt between May and June and with significant floods in summer and early autumn due to persistent rainfall.

In the catchment forests cover just 7% of the total basin (*Picea abies* and *Larix decidua*) and only in the lower part of the area. The major part of the catchment features Alpine grasslands (61%) and shrubs (18%). Scree deposits on talus slopes are usually distant and disconnected from the main channel, and the stream normally has low to moderate sediment supply conditions (Mao et al., 2009). The Rio Cordon creek has developed its main channel mainly over quaternary moraine and scree deposits. The average slope of the stream is ~ 17% featuring a rough channel bed with a step-pool morphology and large boulders. The grain size distribution (GSD) of channel bed surface was estimated in August 2014, assessing the percentiles $D_{16}/D_{50}/D_{84}$ equal to 29/114/358 mm, respectively. Comparing the surface GSD with the sub-surface GSD (D_{50ss}= 38 mm; D_{84ss}= 125 mm) appears evident the high degree of channel bed armouring (Mao et al., 2010). The bankfull discharge was estimated by Lenzi et al. (2006b) as equal to 2.30 $m^3 s^{-1}$.

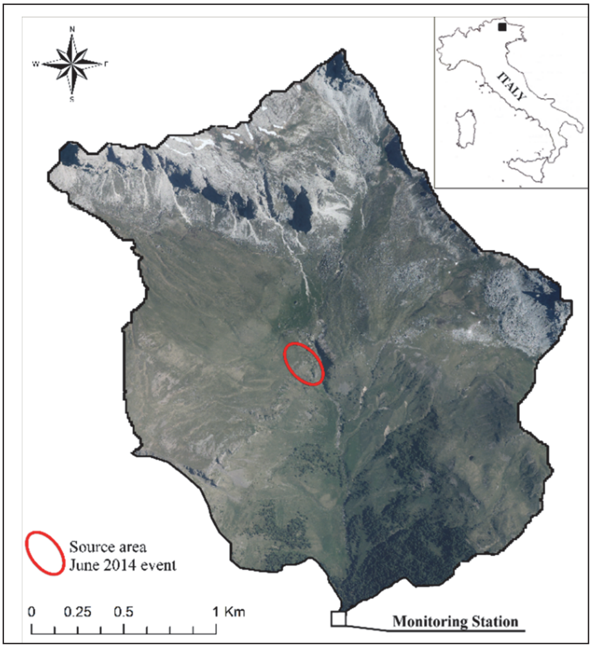

Fig. 1 - *Rio Cordon study basin, the red circle shows the source area of June 2014 bedload event*

Since 1986, the Rio Cordon basin is equipped with a permanent monitoring station, realized by Veneto Region – Experimental Centre of Arabba and currently managed by ARPA Veneto. Specifically, the station is located at an altitude of 1763 m a.s.l., just below the upper limit of the forest. The numerous devices installed for monitoring water discharge, bedload transport and suspended sediment concentration, among other parameters, have been described in detail by Rainato et al. (2016). Basically, the station mainly consists of an inlet flume, an inclined grid, a storage area for bedload material, an outlet flume and a settling basin for the suspended load material. The water discharge is continuously measured (at 1 hr intervals, 5 min during floods) by 2 water level gauges and 1 sharp-crested weir, while 2 light-scatter turbidimeters enabled the suspended load to be recorded. Once transported, the coarse material is deposited in a storage area where can be surveyed and investigated. The operating of the monitoring station allowed to record and analyze 31 bedload events (Rainato et al., 2016). Such events exhibited a wide range of magnitude, ranging from exceptional (i.e. September 1994, recurrence interval RI > 100 ys) to near-bankfull floods (i.e. November 2012, RI = 1.7 ys). The station is also equipped with two meteorological stations, located at different altitude (i.e. 1763 and 2130 m a.s.l, respectively) enabling to record data about rainfall, air temperature, atmospheric pressure, relative humidity and solar radiation.

2.2 Bedload, grain size and source area investigation

The bedload event occurred in June 2014 was investigated using the data produced by the monitoring station. The hydrological features were assessed using the 5-min discharge data, enabling to determine peak of water discharge (Q_{PEAK}), duration of bedload event (T_{BL}), discharges in correspondence of which the bedload started and ended (Q_{START}, Q_{END}), and consequently the effective runoff (ER). To determine the amount of coarse material transported and deposited into the storage area, a Terrestrial Laser Scanner (TLS) was used. The point cloud produced by the survey permitted to create a Digital Elevation Model (DEM) of bedload volume characterized by a cell size = 2 cm. To assess the grain size characteristics of bedload, the amount conveyed into the storage area was investigated using the grid by number method. As regards the source area, once identified, the zone was mapped using a differential Global Position System (DGPS) device, with an average vertical quality equal to 2 cm.

3. Results

During 2014, a significant bedload event occurred on June, 9. The transport took place during a mixed snowmelt-rainfall event, that triggered a Q_{PEAK} equal to 2.06 $m^3 s^{-1}$ (RI = 1.7 ys). During the antecedent hours 16.60 mm of precipitation were recorded by the meteorological station (Fig. 2), mainly concentrated in the afternoon hours. Due to the abundant snowfalls that occurred in winter, in 2014 the snowmelt period lasted until June. In the hydrograph reported in figure 2, the typical daily fluctuations in the discharge due to the snowmelt phase can be noted.

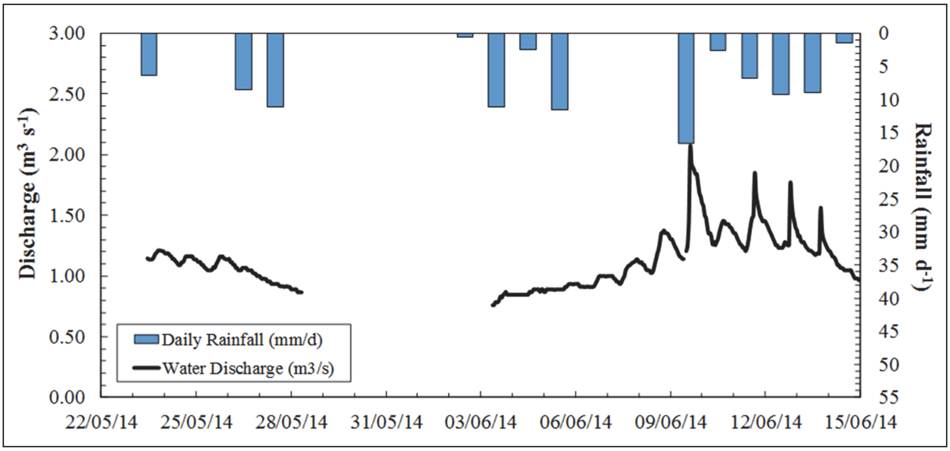

Fig. 2 - *Discharge and rainfall time series during the June, 9 bedload event*

As regards the bedload event, the transport lasted for about 14 hours, between the 2.10pm on June, 9 to 4.10am on June, 10. Specifically, the transport started with a discharge equal to 1.5 $m^3 s^{-1}$ and ending to 1.4 $m^3 s^{-1}$ (Tab. 1). Consequently, the effective runoff (*ER*) is 16.6 10^3 m^3. Very significant is the volume transported downstream, equal to 65.3 m^3 (Fig. 3). Considering the bedload volume, the flood of June 2014 is the sixth most important recorded event. Due to the volume transported, also the bedload transport rate (*BLr* = 4.7 $m^3 h^{-1}$) appears quite high. In this sense, merely the events on October 1987, September 1994 and October 1998 exhibited higher rates.

Thanks to the post-flood survey, the source area was detected. A debris flow channel located in the median part of the basin, on the right side, was identified as source area. The field evidences (i.e. traces of moved loam) showed the occurrence of a debris flow along this lateral channel (Fig. 3). The material produced by the gravitational process reached the main channel approximately 1300 m upstream the monitoring station (Fig. 1).

The grain size distribution of the bedload material was evaluated using the grid by number method. The largest particle detected in the storage exhibited by a *b-axis* equal to 230 mm. Thanks to the collection of 262 clasts, the GSD percentiles were estimated as: D_{16} equal to 16 mm, D_{50} is 41 mm, D_{84} is equal to 64 mm while D_{90} is 76 mm (Fig. 4). In this sense, the GSD characterization demon-

Q_{PEAK} ($m^3 s^{-1}$)	*RI* (years)	*BL* (m^3)	Q_{START} ($m^3 s^{-1}$)	Q_{END} ($m^3 s^{-1}$)	T_{BL} (h:m)	*BLr* ($m^3 h^{-1}$)	*ER* ($10^3 m^3$)
2.06	1.7	65.3	1.5	1.4	14:10	4.7	16.6

Tab. 1 - *Main characteristics of the floods occurred on June,9 2014. Q_{PEAK} is the peak of water discharge ($m^3 s^{-1}$); RI the recurrence interval (years); BL the bedload (m^3); Q_{START} and Q_{END} are the discharges in correspondence of which the bedload started and ended, respectively; T_{BL} is the bedload duration; Blr is the mean bedload intensity ($m^3 h^{-1}$); ER the Effective Runoff volume ($10^3 m^3$)*

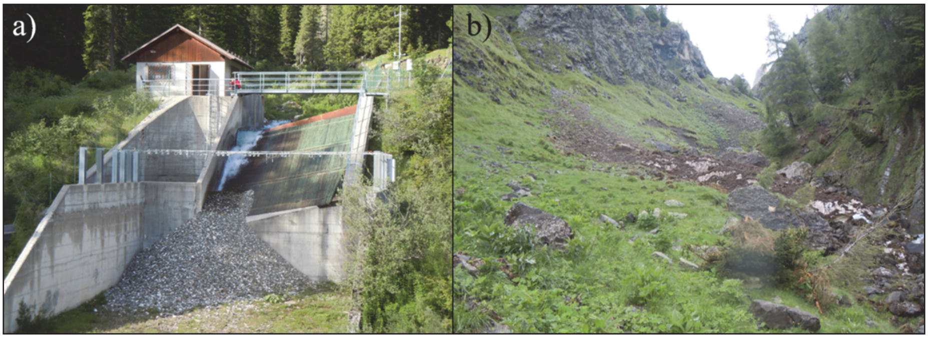

Fig. 3 – *June, 9 bedload event: coarse material transported to the monitoring station (a) and the source area (b)*

strated that the transported material consisted mainly in a coarse gravel (pebble) with some small cobble, clearly differing from channel-bed material (Fig. 4). The bedload volume transported by the June 2014 event was characterized also in terms of sub-surface GSD. For this purpose, the sampling was carried out moving the superficial clasts, for a depth equal to 2 $D_{MAX.}$ The remaining surface represents the sub-surface on which the grid by number method was applied. On the whole, 275 particles were measured and the results of the GSD shows the percentiles $D_{16ss}/D_{50ss}/D_{84ss}/D_{90ss}$ equal to 25/43/79/85 mm, respectively (Fig. 4).

4. Discussion

In terms of hydrological features, the June 2014 bedload event appears triggered by a mixed snowmelt-rainfall flood. Notwithstanding the moderate rain-

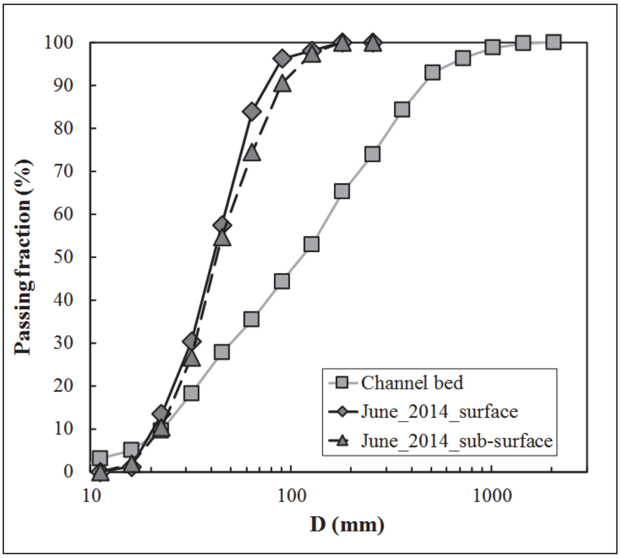

Fig. 4 - *Grain size distributions concerning the bedload material (surface and sub-surface) mobilized by June 2014 flood and the channel bed surface*

fall occurred on June, 9 (16.60 mm) a near-bankfull Q_{PEAK} was triggered. In this sense, the rainfall occurred during the afternoon hours, increasing the already significant runoff due to the snowmelt. If compared with the floods recorded in the Rio Cordon basin (Rainato et al., 2016), the effective runoff characterizing the June 2014 bedload event (ER = 16.6 10^3 m^3) appears rather low. This, combined with the fairly high bedload transport rate (BLr = 4.7 m^3 h^{-1}), suggests the availability of a significant amount of coarse material, then rapidly washed out.

The post-flood surveys allowed to identify a lateral debris-flow channel as the main source area. In line to what observed in the Rio Cordon during the 2001 and 2012 events (Lenzi et al. 2003; Rainato et al., 2013), this evidence demonstrated how the June 2014 bedload event was supplied by a hillslope event, which provided a large quantity of loose sediment to the main channel, then easily transported downstream. The GSD analysis of bedload volume highlighted that sub-surface material was coarser than superficial one, suggesting that fine particles were transported during the recession limb of the event, while the coarser fraction was mobilized in the antecedent phase of hydrograph. Therefore, the analysis allowed the transport dynamic and the competence that characterized the different phases of the bedload event to be assessed. Overall, the GSD transported by the June 2014 bedload event appears fully comparable to the grain size distribution entrained by the November 2012 flood, i.e. $D_{16}/D_{50}/D_{84}/D_{90}$ equal to 23/38/70/79 mm. Such evidence demonstrated how the most recent bedload events (i.e. November 2012, June 2014), both supplied by hillslope collapses, transported similar material in terms of particle size. If compared to the channel-bed material, the sediments mobilized by bedload events are clearly finer (Fig. 4). Such result appears consistent with the concept of "traveling bedload" (Yu et al., 2009), that typically occurs in the mountain armoured channels when supplied by hillslopes processes. Local injection of sediment triggers bedload, but only the finer fraction is transported, not interacting with the armour layer, while the coarser sediments are deposited on the channel bed (Schuerch et al., 2006). In light of the results achieved (i.e. GSD bedload vs GSD channel bed, low *ER*, material rapidly washed out with high *BLr*, armour layer), the traveling bedload appears the main transport process in the current sediment supply condition of Rio Cordon. Particularly, the bedload magnitude is related to the hillslope collapses magnitude, which in turn seems to be linked to the climatic conditions (i.e. rainfall, snow coverage and extent of snowmelt). In this sense, the magnitude of June 2014 hillslope process appears particularly significant, as triggered the sixth most important recorded bedload event.

5. Conclusions

The monitoring program active in the Rio Cordon since 1986 enabled to investigate the June 2014 bedload event. The results achieved demonstrate how the Rio Cordon creek, despite a channel bed strongly armoured, can transport large amounts of sediment also during near-bankfull flood. In particular, the

June 2014 bedload event mobilized more than 65 m^3 of coarse material, representing the sixth most important recorded event. The post-flood surveys identified a lateral debris flow channel as the main source area.

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