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Original Research

Near-bankfull floods in an Alpine stream: Effects on the sediment mobility and bedload magnitude

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A B S T R A C T

In a mountain environment, the transport of coarse material is a key factor for many fields such as geomorphology, ecology, hazard assessment, and reservoir management. Despite this, there have been only a few field investigations of bedload, in particular using multiple monitoring methods. In this sense, attention has frequently focused on the effects of “high magnitude/low frequency floods” rather than on “ordinary events”. This study aims to analyze the sediment dynamics triggered by three high-frequency floods (recurrence interval “*RI*” between 1.1 and 1.7 yr) that occurred in the Rio Cordon basin during 2014. The flood events were investigated in terms of both sediment mobility and bedload magnitude. The Rio Cordon is an Alpine basin located in northeastern Italy. The catchment has a surface area of 5 km^2, ranging between 1763 and 2763 m above sea level. The Rio Cordon flows on an armored streambed layer, with a stable step-pool configuration and large boulders. Since 1986, the basin has been equipped with a permanent station to continuously monitor water discharge and sediment flux. To investigate sediment mobility, 250 PIT-tags were installed in the streambed in 2012. The 2014 floods showed a clear difference in terms of tracer displacement. The near-bankfull events showed equal mobility conditions, with mean travel distance one order of magnitude higher than the below-bankfull event. Furthermore, only the near-bankfull events transported coarse material to the monitoring station. Both events had a peak discharge up to 2.06 $m^3 s^{-1}$, but the bedload transport rates differed by more than one order of magnitude, proving that under the current supply-limited condition, the bedload appears more related to the sediment supply than to the magnitude of the hydrological features. In this sense, the results demonstrated that near-bankfull events can mobilize large amounts of material for long distances, and that floods of apparently similar magnitude may lead to different sediment dynamics, depending on the type and amount of sediment supply.

1. Introduction

Bedload transport in mountain streams strongly affects downstream sediment delivery (Liébault et al., 2016), channel stability (Baewert & Morche, 2014), and, thus, the assessment of hazard areas along river corridors. Within the context of the European Union (EU) water framework directive, an accurate assessment of sediment transport is required for flood risk mapping and management. Also, from an ecological point of view, in many mountain regions the spawning habitats of fishes and the lifecycle of micro- and macro-invertebrates appear to be strongly affected by bedload (Vazquez-Tarrio & Menendez-Duarte, 2014; Wohl, 2015). However, bedload is notoriously difficult to measure in the field as the high-energy and impulsive nature of bedload make its investigation and assessment a challenging task. This is particularly evident in mountain streams, where several factors make bedload processes differ from those in lowland rivers. In addition to the high gradient, sediment mobility is strongly influenced by the highly heterogeneous streambed material, which results in factors such as grain sorting (Hammond et al., 1984), particle size interactions and hiding-protrusion effects (Ashworth & Ferguson, 1989), low relative roughness (Bathurst et al., 1983), presence of a strong armor layer (Lenzi, 2004), embedding and exposed patches (Bathurst, 2013), and slope (Lamb et al., 2008). In addition to the magnitude of a flood event (Lenzi et al., 2006a), the bedload transport rate is strongly related to sediment supply conditions (Beylich & Laute, 2015; Downs et al., 2016; Liébault et al., 2012; Recking, 2012; Schwendel et al., 2011), and hillslopes-channel coupling (Cavalli et al., 2013). These complex conditions are

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reflected in the poor performance of bedload predictive equations, which are usually derived from laboratory experiments or specific field sites (Yager et al., 2015).

The availability of field data also is quite scarce, with a lack of monitoring programs maintained at the same study site over long periods. Nevertheless, several direct and indirect monitoring methods have been developed in the recent decades, enabling valuable field data to be obtained about bedload (Habersack et al., in press; Krein et al., 2016; Mao et al., 2016; Rickenmann et al., 2012). By collecting the sediment that is transported over a certain time interval, bedload traps allow the rate and grain size of coarse material mobilized to be analyzed (Bunte et al., 2008). The devices can be installed in permanent monitoring stations, enabling analysis over long time scales (Rainato et al., in press), or can be used as moving traps, focusing on short time periods (Mao et al., 2008).

The tracers method consists of individual particles that are collected, painted, and replaced in the channel (Fraley, 2004). Single-grain tracers can be used to investigate sediment travel distances (Olinde & Johnson, 2015), virtual velocity (Houbrechts et al., 2015), bedload transport rates (Dell'Agnese et al., 2015), threshold conditions (Lenzi et al., 2006b) and to estimate bedload volumes during flood events (Liébault & Laronne, 2008; Schneider et al., 2014), and can be integrated with information obtained from traps (Ferguson & Wathen, 1998). Recently, the application of the Radio Frequency Identification technology (RFID) to sediment tracing has allowed buried tracers to be detected, increasing the recovery rates (Lamarre et al., 2005). In particular, to achieve continuous tracing, the particles can be embedded with Passive Integrated Transponders (PIT) programmed with a unique identification code (ID). In terms of investigation, the PIT-tags are small, not too expensive, and can potentially allow long-lasting monitoring. The information obtained from these tracers can be extremely useful since the bedload transport rate in mountain channels seems to depend on width and depth of bed scouring, as well as travel distances of the sediment particles (Schneider et al., 2014).

Here the results obtained from an investigation of near-bankfull floods that occurred in 2014 in the Rio Cordon instrumented basin (Eastern Italian Alps) are presented. Three high-frequency bedload events occurred in May, June, and November. They were investigated in terms of both bedload amount (i.e. coarse material trapped by the monitoring station) and analysis of the displacements of 250 PITs installed along the streambed. Despite the relatively low magnitude of flood events, the complex features that occurred in terms of sediment supply and hydraulic forcing enabled different sediment dynamics to be clearly observed and analyzed.

2. Study area and methods

2.1. Rio Cordon study site

The Rio Cordon basin (Dolomites, northeast Italy) drains a surface of 5 km^2, ranging from 1763 to 2763 m a.s.l. (Fig. 1). Alpine climatic conditions prevail in the watershed, with a prevalent nivo-pluvial runoff regime. The long-term mean annual precipitation is 1150 mm. Quaternary moraines and scree deposits are very common throughout the basin, but are mainly disconnected from the drainage network. In terms of land use, most of the catchment is covered by Alpine grasslands (61%) and shrubs (18%). Barely 7% of the area is forested, while 14% is bare land. Talus slopes, shallow landslides, eroded stream banks, and debris flow channels are the main sediment source areas, covering 5.2% of the basin (Lenzi et al., 2003). Due to distance and the decoupling of such sources, the drainage network normally has a low/moderate sediment supply. The Rio Cordon has an average slope of 17%, a rough streambed with a step-pool configuration and large boulders. The grain size distribution (GSD) of the streambed surface is characterized by $D_{16}=29$ mm, $D_{50}=114$ mm, and $D_{84}=358$ mm (where D_x means the sediment diameter for which x percent of the sediment is finer). Overall, the stream has a well-developed armor layer, with the sub-surface GSD ($D_{50ss}=38$ mm) clearly finer than the surface material. Based on field observations, Lenzi et al. (2006a) defined the bankfull discharge as 2.30 m^3 s^{-1}.

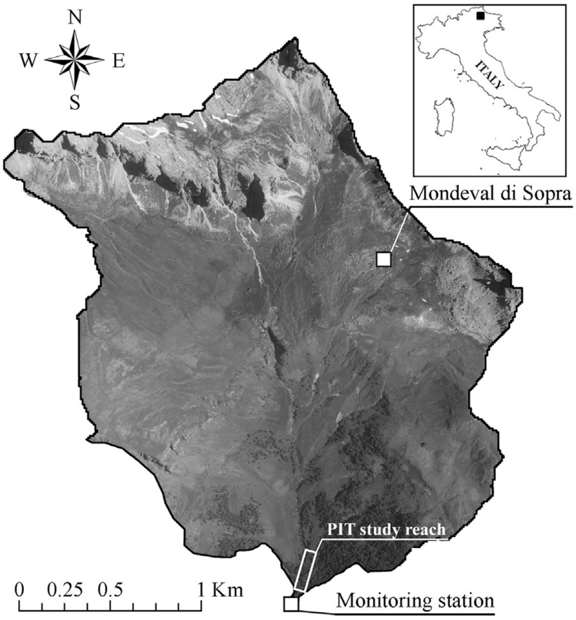

Fig. 1. The Rio Cordon study site. "Mondeval di Sopra" identifies the upstream meteorological station, while "Monitoring station" identifies both the sediment transport monitoring and the downstream meteorological station.

Since 1986, a permanent monitoring station has recorded water discharge, bedload and suspended load of the Rio Cordon stream (Fattorelli et al., 1988). The station 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 (Picco et al., 2012). The water discharge is measured hourly by two water level gauges and a sharp-crested weir. During flood events, the sampling interval decreases to 5 min. The inclined grid (60% longitudinal slope) enables the coarse sediment (>20 mm) to be separated from water and fine material. Once separated, the coarse material sinks into the storage area, where 24 ultrasonic sensors continuously measure the amount transported. Turbidimeters were installed in the inlet and outlet channel to measure the suspended load. Two meteorological stations in the study basin record air temperature, atmospheric pressure, relative humidity, solar radiation and rainfall hourly. The upstream meteorological station "Mondeval di Sopra" is located at 2130 m above sea level, while downstream the climatic conditions are measured at 1763 m a.s.l., in proximity to the monitoring station (Fig. 1). The Rio Cordon instrumented basin is managed by ARPA Veneto, Regional Department for Land Safety.

2.2. Methods

Data collected at the monitoring station were used to analyze the flood events in terms of bedload magnitude. The 5-min interval discharge data were used to describe the hydrological features of the floods, i.e. hydrograph, peak discharge (Q_{PEAK}), and duration of the events. In the case of a bedload event, the effective runoff (ER, 10^3 m^3) was also estimated. The effective runoff is

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