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An update of the magnitude–frequency analysis of Rio Cordon (Italy) bedload data after 25 years of monitoring

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Abstract Quantification of bedload transport in high-gradient mountain streams is important, but field data necessary to test transport models are scarce. In the present work, we describe the experimental station for monitoring water and sediment fluxes built in 1985 on the Rio Cordon (Eastern Italian Alps), a small step-pool channel. The measuring station consists of an inclined frame that separates (at 20 mm truncation) fine and coarse sediments, which are continuously measured for accumulations by two turbidimeters. The 25-year dataset acquired, which comprises high-magnitude/low-recurrence flood events, has allowed a magnitude–frequency analysis of bedload volumes. Results from a combined frequency analysis of peak water discharge and total bedload volumes based on the 25 events are presented, focusing on discrepancies between recurrence intervals of peak discharge and bedload volume for each event. In addition, the integration between the sediment transport dataset and the repeated surveys of sediment sources and of channel changes has permitted to assess the geomorphic effectiveness of different flood events. The Rio Cordon measuring facilities have provided excellent data and valuable insights into the bedload dynamics of steep streams throughout its 25 years of operation, thanks to the close collaboration between the ARPAV-Veneto Region and the Department Land and Agro-forest Environments (University of Padova). However, the maintenance costs of the station are not trivial and may impact its future "vitality". At the same time, improvement of the present instrumentation and installation of novel technology would make the station an ideal location for calibrating surrogate techniques for sediment transport monitoring.

Key words bedload; steep channels; sediment supply; frequency analysis; step pool; alpine torrents

INTRODUCTION

Sediment transport in steep mountain streams can occur as bedload or debris flows, depending on basin geomorphological and sediment supply conditions (Fattorelli *et al.*, 1988; Lenzi *et al.*, 1990, 1999, 2003, 2006a, 2011; Rickenmann *et al.*, 1998; Bathurst *et al.*, 2003, 2010; Mao *et al.*, 2005, 2008, 2009; Lenzi, 2006; Segato *et al.*, 2006; Mao & Lenzi, 2007; Rigon *et al.*, 2012). The quantification of bedload transport in steep mountain streams is of major importance for planning hazard mitigation, predicting reservoir sedimentation and understanding morphodynamics of higher-order channels. However, poorly sorted mountain rivers may require infrequent high discharges for the mobilization of the coarsest clast size, thus only a portion of finer (gravel and cobble) particles is likely to be entrained annually (Wohl, 2000; Lenzi, 2004; Yager *et al.*, 2012). The monitoring activity of bedload transport in steep, small (<10 km^2) mountain catchments poses problems that are complex due to the impulsive or high-energy nature of this process, where intense sediment transport can even lead to non-Newtonian flows: hyper-concentrated flows or debris flood (Mintegui *et al.*, 2010; Lenzi *et al.*, 2011).

The short duration and relatively low frequency of occurrence of the events require the implementation of robust and reliable systems for performing direct field observation. Indeed, monitoring activities carried out through permanently installed devices are very costly. However, such experimental sites become extremely valuable when long-term series of data are eventually produced, thus allowing statistically significant analysis and experience-based predictions (Mao *et al.*, 2008; Nitsche *et al.*, 2011; Yager *et al.*, 2012). Experimental measuring stations thus represent precious tools for the scientific community as well as for the agencies dealing with torrent control and land-use planning. This paper presents the experimental facility of the Rio Cordon (Eastern Italian Alps), summarizes the results gained during 25 years of operation, and discusses the costs and drawbacks of the technology deployed.

STUDY BASIN AND MEASURING STATION

The Rio Cordon is a boulder-bed, step-pool stream draining an area of 5 km^2. Due to its high elevation and past use for cattle grazing, forests cover only the lower part of the catchment (7% of the area). Alpine grasslands dominate (61%), followed by shrubs (18%) and bare land (14%). The bedrock mainly consists of dolomites, volcaniclastic conglomerates and tuff sandstones. Quaternary deposits are also common. The Rio Cordon's mean channel slope is 13.6% and the longitudinal channel profile displays an alternation of high-gradient and low-gradient stretches. The average bed-surface grain size distribution is characterized by D16 = 37 mm, D50 = 119 mm and D84 = 357 mm (Lenzi *et al.*, 2004). Some reaches of the Rio Cordon channel feature step-pool morphology (Fig. 1). Through detailed field surveys of the longitudinal profile carried out before and after floods of different magnitudes, Lenzi (2001) demonstrated that the step-pool sequences are bed structures that fail only during low-frequency intense flood events. In the Rio Cordon, active sediment sources, i.e. bare slopes, shallow landslides, eroded stream banks and minor debris flow channels, cover about 5% of the basin area. However, about 50% of the total sediment source area is located upstream of a low gradient belt where sediment deposition takes place, thus making sediment supply from the upper part of the basin to be of minor relevance (Dalla Fontana &

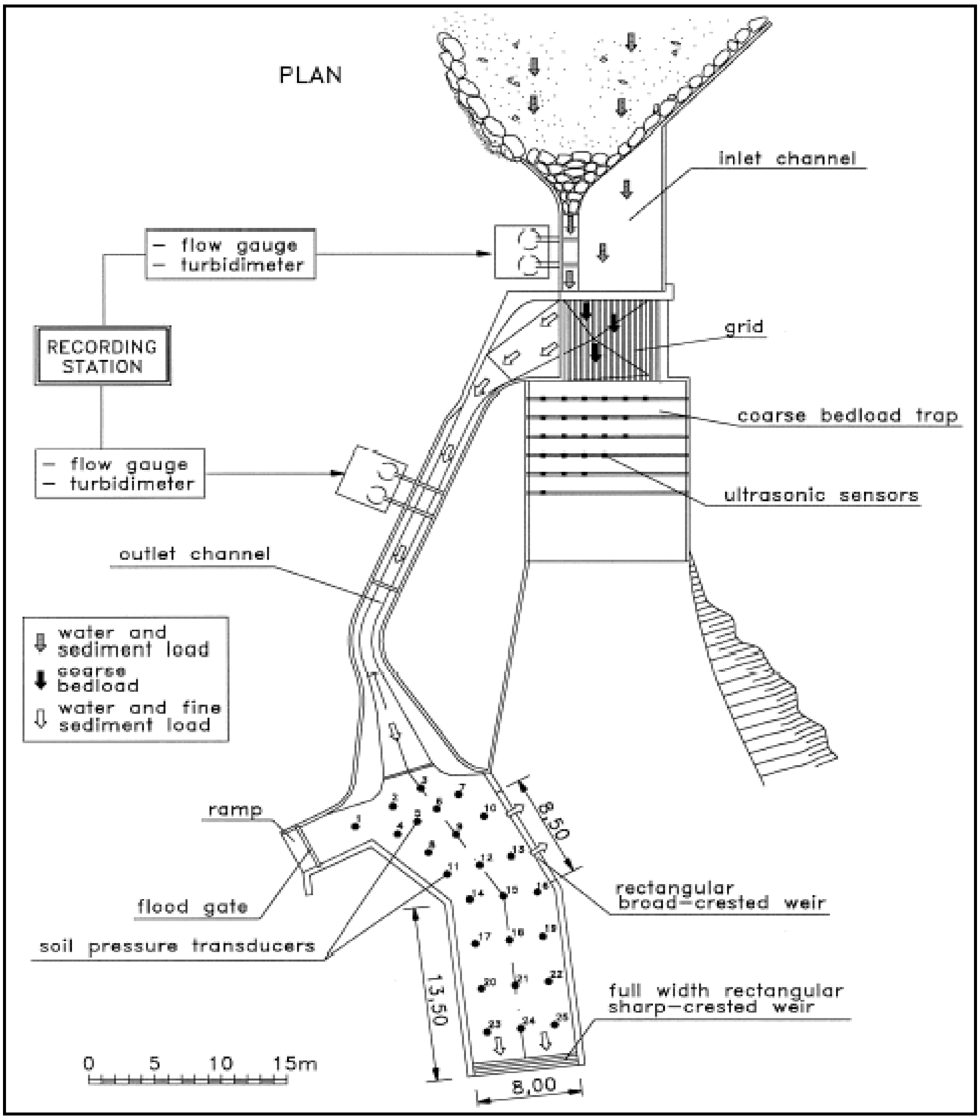

Fig. 1 Plan view of the Rio Cordon bedload measuring station (after Lenzi *et al.*, 2004).

Marchi, 2003; Lenzi *et al*., 2004). The generally limited sediment availability within the main channel can occasionally be increased either during low-frequency events that are able to remove the bed armour layer (as during the 1994 flood), or by minor mud flows and debris flows entering the main channel from the steeper tributaries (Lenzi *et al*., 2004).

A station for monitoring water discharge, suspended sediment and bedload transport has been operating since 1986 in the Rio Cordon. Measurements are taken by separating coarse grains (minimum size 20 mm) from water and fine sediments (Lenzi *et al*., 1999, 2004). The measuring station consists of an inlet flume, an inclined grid where the separation of coarse particles takes place, a storage area for coarse sediment deposition, and an outlet flume to return water and fine sediment to the stream (Fig. 1). The volume of bedload is measured at 5-min intervals by 24 ultrasonic sensors fitted on a fixed frame over the storage area (Lenzi *et al*., 1999, 2004). Suspended sediment is measured by two turbidimeters: a Partech SDM-10 light absorption and a Hach SS6 light-scatter instrument (Lenzi & Marchi, 2000). Flow samples are gathered automatically using a Sigma pumping sampler installed at a fixed position in the inlet channel. Overall, 25 bedload events characterized by bedload transport (grain size >20 mm) were recorded by the Rio Cordon station from 1986 to 2006 (Lenzi *et al*., 2004; Mao *et al.,* 2008). On 14 September, 1994, an intense flood featuring a peak water discharge of 10.4 $m^3 s^{-1}$ and a peak bedload transport rate of about 157 kg s^{-1} (25 kg $s^{-1} m^{-1}$) was recorded (Lenzi *et al*., 2004). Such a high-magnitude event features the typical flash-flood pattern, i.e. a very high peak flow rate, a very short duration (4 h), and 900 m^3 as total bedload volume. The coarsest boulders (around 1 m) of the bed surface were entrained and transported to the station. Most sediment was supplied by the channel-bed after the bed armour layer was removed, and channel banks, plus some point sources on the catchment slopes (Lenzi *et al*., 2004). Such a high-magnitude, low-frequency event has represented a geomorphic threshold for the Rio Cordon basin, since it has altered the stream bed geometry (Lenzi, 2001) and the sediment-supply characteristics of the basin as a whole (Lenzi *et al*., 2004). Comparing the bedload/flow rate relationship and the ratio between bedload volume and effective runoff for the whole floods, Lenzi *et al*. (2004) demonstrated the increase in sediment availability and the consequent increase in bedload transport after the 1994 low-frequency event. During "ordinary" flood events, bedload showed intensities of up to 30 kg s^{-1} (4.6 kg $s^{-1} m^{-1}$), but most bedload rates ranged from 0.1 to 3 kg s^{-1} (0.03–0.6 kg $s^{-1} m^{-1}$) (see Lenzi *et al*., 2004) for a more detailed description of bedload intensities for different durations and recurrence intervals floods). From 2007 to 2011 only low small floods (up to 1.2 $m^3 s^{-1}$) were recorded with very small associated bedload volumes (lower than 1 m^3).

FREQUENCY ANALYSIS OF FLOOD EVENTS: PEAK DISCHARGE AND BEDLOAD VOLUME

In order to evaluate their frequency of occurrence, the return interval of each flood was estimated from values of annual maximum instantaneous water discharge over the 25 years, selecting for each year the largest event in the case of multiple floods. Using the software STATISTICA 6.1, the best fitting distribution and its parameters were determined. Both Gumbel and Lognormal distributions were found to fit reasonably well. The recurrence intervals calculated by the two equations do not differ substantially (on average ±8%). The recurrence interval of the September 1994 event is around 76 years according to the Lognormal distribution (Fig. 2). The return intervals of bedload volumes were also estimated using the annual maximum volumes (bulk measure). Weibull and Lognormal distributions were the best fitting. Again, the recurrence intervals do not differ substantially (on average ±10%) between the two distributions. Similar to the peak water discharge analysis, the Lognormal distribution was selected to calculate the recurrence intervals of bedload volumes and the recurrence interval of bedload transport of the September 1994 flood is around 51 years according to the Lognormal distribution (Fig. 2).

In Fig. 3 a graphical comparison between return intervals for water discharge and bedload volumes is shown. Most post-1994 points fall above the 1:1 line, whereas most pre-1994 points

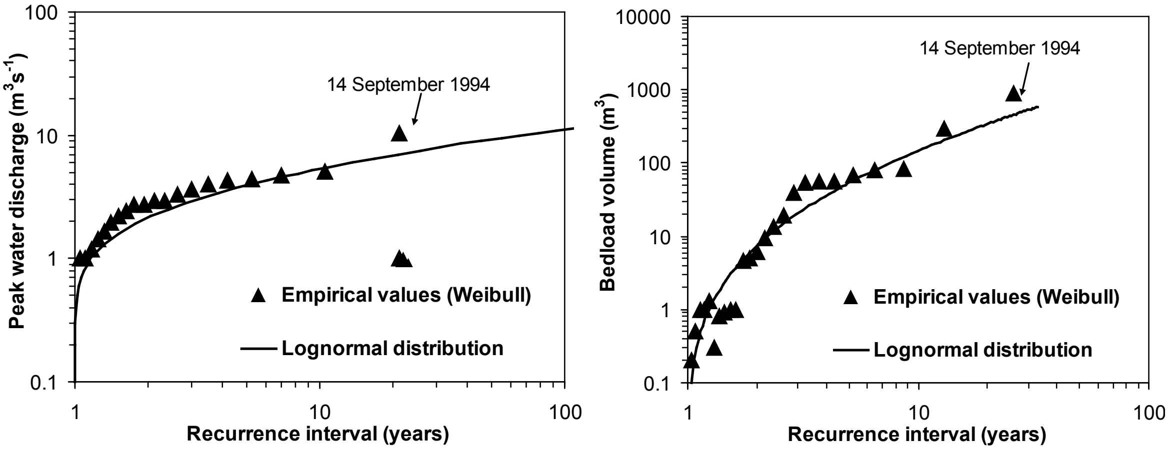

Fig. 2 Magnitude-frequency relationship for annual maximum peak discharge (on the left), and magnitude-frequency relationship for annual maximum bedload volume (on the right). The bedload volumes are expressed as bulk measure (including voids).

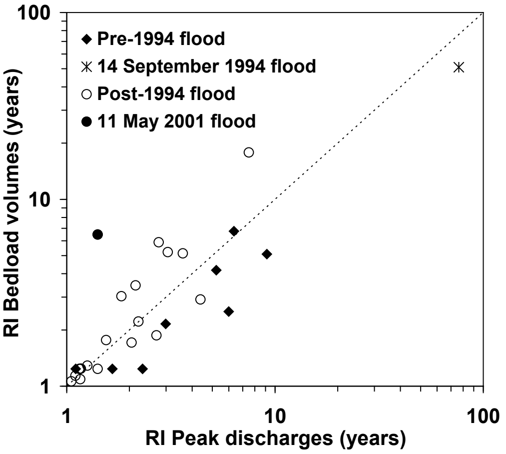

Fig. 3 Comparison of recurrence intervals referring to liquid peak discharge and total bedload volumes for each recorded flood event.

fall below the line. Indeed, the 1994 flood with a peak water discharge of 10.4 m^3 s^{-1} and an hourly averaged bedload intensity of 225 m^3 h^{-1} appears to represent a threshold for bedload transport in the Rio Cordon basin. After the 14 September 1994 flood event, a survey of sediment source areas was performed and extensive areas of reactivated sediment sources, bank erosion and several bank failures were documented along the main stream and some tributaries.

TEMPORAL TRENDS IN THE BEDLOAD TRANSPORT

The hydrological and sedimentological data of major flood events recorded in the Rio Cordon between 1986 and 2011 are presented chronologically in Fig. 4, and the limited and unlimited sediment supply periods, separated by the September 1994 event, are highlighted. The effective runoff (Re), determined for each flood as the hydrograph volume exceeding the detected threshold discharges from the beginning to the end of the bedload transport, provides a means to normalize total bedload volumes (BL) and thus allows us to infer temporal trends in the bedload yields. Figure 4 shows a semi-logarithmic plot of the ratio BL/Re (with Re expressed as 10^3 m^3) for each flood. The BL/Re ratio exhibits two decreasing trends over the 1986–1993 and 1995–2011 periods, and the BL/Re ratio of the September 1994 flood is 1 order larger than the other floods,

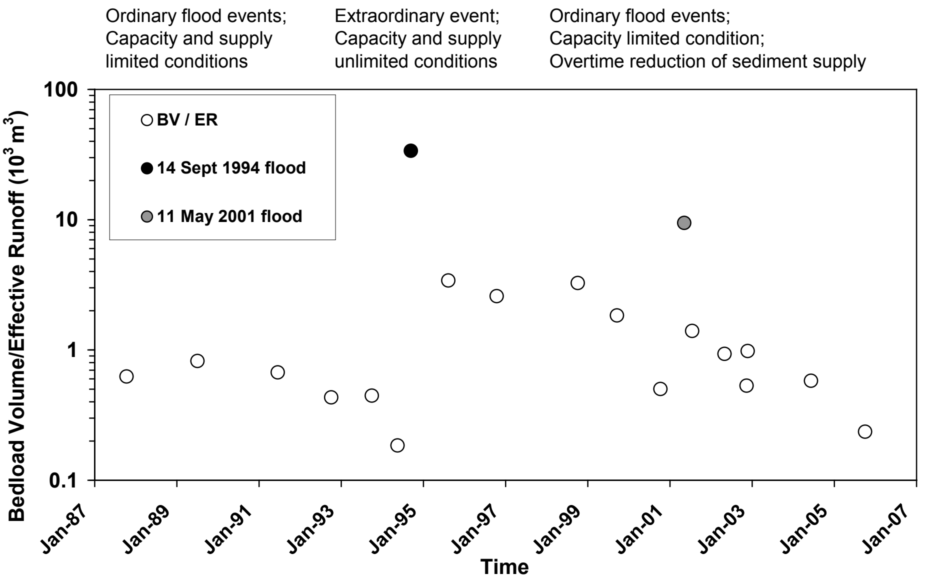

Fig. 4 The ratio bedload volume/effective runoff over the 25 years of records.

except for the May 2001 event. During the 1994 extreme event the channel bed was the main source of sediment for bedload transport (Lenzi *et al.,* 2003, 2004), mainly because such a large discharge was able to destroy the streambed armour layer which had formed over the years. Also during the September 1994 flood, old sediment sources were reactivated and new ones were created. Fine and medium size sediments eroded from the hillslope were stored in the stream network as the flood waned and were subsequently removed and transported downstream by ordinary floods in 1996, 1998 and 2000.

Similarly, quasi un-limited sediment supply conditions occurred in the Rio Cordon as a consequence of the 2001 mud flow. In addition to the May 2001 event's high bedload transport, it is estimated that the small July 2001 flood mobilized 21 m^3 of bedload material from the newly formed fan. The three floods in 2002 show high sediment loads too, and this may be partly an inheritance of the May 2001 mud flow, and the area close to the measuring station during the November 2002 event might have contributed considerably to this flood's high bedload transport.

MAINTENANCE COSTS AND DRAWBACKS OF THE RIO CORDON FACILITY

The station generally operates 40–45 weeks per year and is closed in winter due to the deep snowpack and the irrelevant flows. On average, the ordinary maintenance requires 250–300 hours per year. The station is normally visited by technicians once a week, but all the data collected are radio-transmitted daily to the Arabba Avalanche Centre (public agency run by the Veneto region). The ordinary weekly operations consist of sensor check-up (of those giving erroneous data during the previous week), manual cleaning of turbidimeters, manual pH and conductivity measurements, manual sampling of suspended sediment transport, and maintenance of other complementary instruments (hydrometer, hygrometer, pluviometer) that register data on paper. The good access to the station, i.e. a paved road, is crucial to guarantee both ordinary maintenance of the instrumentation, and quick access during the bedload transporting events, typically short, in order to directly observe their phenomenology. Although the station has overall fulfilled its required tasks, there are several aspects that could be improved to allow more accurate bedload measurements. Fluctuations in the volume data produced by the ultrasonic sensors placed above the bedload storage area are partly caused by wind. A simple shielding structure over and beside the sensor would avoid swinging and protect them from adverse weather conditions. The most expensive maintenance is often related to these sensors.

The roof above the storage area could be an appropriate location for a fixed video camera and a spotlight in order to continuously record the formation of the sediment mound, thus allowing inference of the transported sediment size at each flood stage. The video camera needs to be programmed to operate when water discharge exceeds the same threshold as for ultrasonic sensor activation. The bottom of the bedload storage area is not cemented; if it was lined with concrete it would lead to more precise ultrasonic measurements and simpler post-flood bedload removal.

The rectangular sharp-crested weir located at the downstream end of the fine sediment retention basin is at present too wide to allow accurate measurements of flow rates <0.1 m^3 s^{-1}. A V-shaped weir in conjunction to the rectangular weir would permit a more precise quantification of low flows. In order to increase the accuracy of discharge measurements during high flows, the inlet channel upstream of the station should be extended for about 5 m to avoid the formation of standing waves disturbing the flow gauging system.

Finally, the Rio Cordon facility provides an ideal means for validating surrogate methods for bedload measurements in steep channels. For example, in the cemented inlet channel, piezoelectric impact sensors such as those installed in several Swiss mountain torrents (Rickenmann *et al.*, 1998; Rickenmann & McArdell, 2007; Yager *et al.*, 2012) could be installed, as well as other passive acoustic devices and magnetic methods. A Birkbeck bedload slot-sampling system, like the one operating in the Nahal Eshtemoa (Powell *et al.*, 2001), could possibly be installed in the narrow cemented outlet channel to measure transport rates of fine sediments, which could then be compared with the total fine sediment accumulated in the retention basin.

FINAL REMARKS

The Rio Cordon measuring facility has provided excellent data and valuable insights into the bedload dynamics of steep streams throughout its 25 years of operation, thanks to the close collaboration between the Arabba Avalanche Center (Veneto Region) and the Department Land and Agro-forest Environment (University of Padova). However, the maintenance costs of the station are not trivial and may impact its future “vitality”. Improvements to the present instrumentation and installation with novel technology would make the station an ideal location for calibrating surrogate techniques for bedload monitoring.

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