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LONG-TERM MONITORING OF BEDLOAD AND DEBRIS FLOWS IN TWO SMALL ALPINE BASINS OF DIFFERENT MORPHOLOGICAL SETTINGS

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ABSTRACT

Sediment transport in steep mountain streams can occur as bedload or debris flows, depending on basin geomorphology and sediment supply conditions. This paper compares two small catchments located in the Eastern Italian Alps (Rio Cordon and Moscardo Torrent) where the dominant sediment transport processes differ substantially. The former hosts a measuring station for water and sediment transport rates operating since 1986, whereas the latter was set up in 1989 to monitor debris-flow events. Differences in sediment dynamics between the two basins are quantitatively investigated by using a magnitude-frequency analysis that highlights the relatively low sediment supply of the Rio Cordon and the unlimited sediment availability in the Moscardo Torrent. This contrasting sediment transfer activity can be attributed to different basin and channel morphologies, which are analyzed in terms of sediment supply conditions and longitudinal profiles curves.

Key words: *Bedload, debris-flow, sediment availability, experimental basins.*

INTRODUCTION

Steep streams draining mountain regions are often characterized by relatively sudden and flashy flood events which often represents a major threat. Sediment transport in small headwater streams (<10 km^2) occurs both as Newtonian (floods with suspended and bedload transport) and non-Newtonian (debris and mud flows) flows, with an intermediate hyperconcentrated flow phase. The differentiation of those different typologies is rarely quantifiable, mainly due to a scarcity of direct measurements. In general, debris flows are masses of sediments saturated with water, where the forces exerted by both components contribute to produce the physics of the flow. Along with thresholds of precipitation and local slope (Gregoretti & Dalla Fontana, 2008), the occurrence of debris flows is controlled by the availability of erodible sediment in the basin and channel system (Bovis & Jakob, 1999) and by the linkage between sediment source areas and channel network. For this reason, debris flow-prone basins are usually unstable, rich in sediment sources and the channels are provided with large amounts of poorly sorted debris. By contrast, in small mountain basins where sediment availability is limited, debris flows occurrence requires a long time interval for sediment recharge. Debris flows in these basins are thus rare, and even major floods are typically characterized by bedload transport with volumetric sediment concentrations usually lower than 10%. The quantification of frequency and sediment volumes (magnitude) transported by debris flows and extreme bedload floods is of crucial importance for hazard assessment, land use planning and design of torrent control interventions (Johnson *et alii*., 1990; Zimmermann *et alii*., 1997; Rickenmann, 1999; Rickenmann & Koschni, 2010). Several authors have derived magnitude–frequency relationships for debris flows (e.g. Marchi & D'Agostino, 2004; Hungr *et alii*., 2008). Differences among the various magnitude-frequency relationships have been related to differences on triggering conditions and debris availability (Van Steijn, 1996). Most of the evaluations of debris flow magnitude and frequency have been conducted by using indirect methods, such as stratigraphic techniques (Blair, 1999), lichenometric methods (Helsen *et alii*, 2002), tree-ring records (Stoffel *et alii*, 2006) or aerial photography interpretation (Jakob *et alii*, 2005). Despite a significant diversity as to their transport mechanics, the monitoring activity of such impulsive, high-energy processes in remote areas poses problems that are similarly complex. Their short duration and relatively low frequency of occurrence require the implementation of robust and reliable systems for performing direct field observation in remote areas. Monitoring activities carried out through permanently installed devices are very costly but are of extreme value when long-term series of data are eventually produced.

In the present paper, the long-term (>10 years) data on sediment volumes in two instrumented channels in the Eastern Italian Alps, will be comparatively analysed. The two study sites are the Moscardo Torrent and the Rio Cordon, both instrumented for the continuous monitoring of sediment transport. The two basins are characterized by comparable size and climatic conditions, but differ as to the typology of the dominant sediment-transporting flows, because the Moscardo Torrent commonly features debris flows in contrast to the Rio Cordon, which is characterized by bedload events.

STUDY BASINS

The Moscardo Torrent and the Rio Cordon are two small headwater basins (around 5 km^2) of the Eastern Italian Alps. Their mean hillslopes gradient is 63% and 52%. Their climatic conditions are typical of Alpine environments, with precipitation (annual average 1660 mm in the Moscardo torrent, and 1100 mm in the Rio Cordon) occurring mostly as snowfall from November to April and snowmelt-dominated runoff in May and June. Short-duration summer floods and floods occurring in early autumn represent important contribution to the flow regime.

MOSCARDO TORRENT

The Moscardo Torrent is a debris-flow channel, whose catchment drains an area of 4.1 km^2. The bedrock geology of the basin is composed of Carboniferous flysch, with highly fractured and weathered shale, slate, siltstone, sandstone and breccias. Quaternary deposits, mostly consisting of scree and landslide accumulations, are common in the basin. The presence of a deep-seated gravitational deformation at the valley head, the loosened rock mass quality and its highly shattered state make the steep slopes of the basin prone to rockfalls and shallow landslides which supply large amounts of debris into the channel (Marchi *et alii*, 2002). Sixty-four percent and 18% of the basin area are covered by conifer forests and shrubs, respectively. Unvegetated areas, which occupy about 18% of the basin, provide most of the debris supplied to the channel network, both in the upper part of the basin and along the main channel. This causes quasi-unlimited amounts of sediment availability, resulting in frequent debris flow events, triggered also by relatively moderate rainstorms. Typical debris flow deposits (lateral levees) are present along the channel, and the frequent occurrence of debris flows prevents the formation of stable bedforms (Fig. 1). The mean gradient of the main channel is about 37%. Concrete check dams were built in the main channel in order to limit bed erosion and to stabilize channel banks in the middle and lower reaches. The debris-flow deposits are poorly sorted and show a wide grain size distribution. Lateral levees and debris-flow lobes mostly consist of pebbles and medium to fine boulders supported in a muddy matrix; larger boulders with an intermediate diameter of 2–3 m are also common. The particle size distribution of debris-flow deposits shows D_{50} ranging approximately from 10 to 20 mm and D_{84} from 500 to 700 mm.

RIO CORDON

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 widespread. The Rio Cordon 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

Fig. 1 - Pictures of the Moscardo Torrent (on the left) and the Rio Cordon (on the right) main channels.

by D_{16} = 37 mm, D_{50} = 119 mm and D_{84} = 357 mm (Lenzi *et alii*, 2004). Some reaches of the Rio Cordon channel feature step-pool morphology (Figure 1). Through detailed field surveys of the longitudinal profile carried out before and after floods of different magnitude, 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, represented by bare slopes, shallow landslides, eroded stream banks and minor debris flow channels, cover about the 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 & Marchi, 2003; Lenzi *et alii*, 2004). The generally limited sediment availability within the main channel can occasionally be increased either during low-frequency events 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 alii*, 2004).

MONITORING DEVICES AND REGISTERED EVENTS

MOSCARDO TORRENT

A debris flow monitoring system, designed and maintained by the Research Institute for the Hydrogeological Protection of the Italian National Research Council (CNR IRPI), has been operating since 1989. The Moscardo Torrent appeared suited for the installation of such a system because it is characterized by frequent debris flows, easy accessibility and by a stable channel on the fan (Marchi *et alii*, 2002). The installed instrumentation includes rain gauges, ultrasonic sensors for the measurement of flow depth, seismic detectors for recording the vibrations caused by the passage of debris flows (Arattano, 1999), and a video camera (Fig. 2). The mean propagation velocity of the front is calculated as the ratio between the sensors (ultrasonic and/or seismic) distance and the time interval between the debris-flow peaks. The methods used for estimating peak discharge and flowing volume from ultrasonic records are discussed in Marchi *et alii* (2002).

In the Moscardo Torrent, 15 debris flow events occurred from 1990 to 1998, 13 of which were recorded by the installed devices (Marchi *et alii*, 2002). Recorded debris flows range from small events (around 700 m^3), which would had probably remained undetected if a monitoring system had not been installed, to intense phenomena with volumes up to about 60,000 m^3. The hydrographs recorded by the ultrasonic sensors show differences from event to event. In particular, surge velocities and hydrograph shapes differ considerably. In some events, debris flows show a single, well-defined wave with a steep front followed by a continuous decrease in flow depth; a few smaller waves may follow the main surge. In other cases, the recession limb is very irregular with abrupt stage fluctuations (Marchi *et alii*, 2002). There are features common to all recorded debris flows and these are the short duration of the event and the presence of a sharp rising limb in the hydrograph, corresponding to the passage of the debris flow front at the monitoring station. The largest debris flow was recorded on July 8, 1996 (Fig. 3). The volume of the flowing mass (water and solid particles), calculated through flow stage measurements and topographical survey, was estimated around 65,800 m^3 (Marchi *et alii*, 2002),

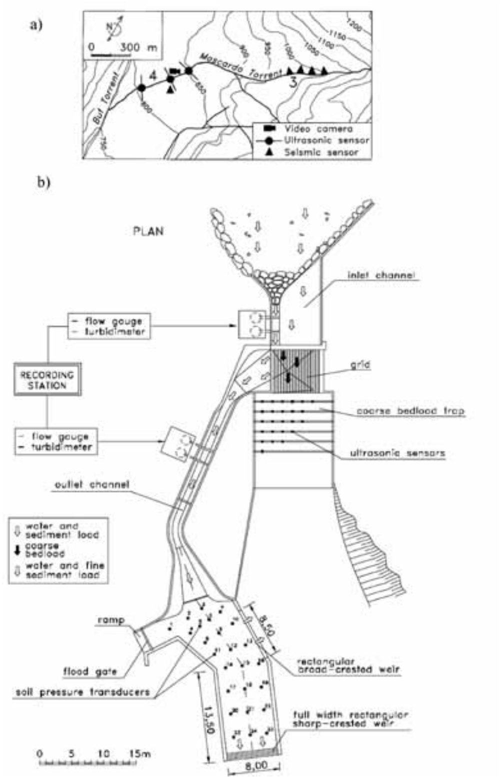

Fig. 2 - Plan view of the instrumented channel stretches (3 and 4) in the Moscardo torrent (a, from Marchi et al.2002) and of the Rio Cordon bedload measuring station (b, from Lenzi et al., 2004). In the Rio Cordon, the grid separates the coarse bedload (D>20mm), which accumulates in a deposit area where ultrasonic sensors monitor its volumetric growth, and the fine sediments, which accumulates in a basin where pressure transducers monitor their accumulation

which is approximately 30% of the total volume recorded in the monitored period. Since 1999, control works have been implemented on the Moscardo Torrent. More grade-control dams have been constructed in the middle and lower parts of the main stream within the basin. On the alluvial fan, the channel was straightened and widened through sediment displacement, and sills were constructed to reduce channel slope. Torrent control works have affected the evolution of the debris flows, so that data collected in the most recent years are not homogeneous with those recorded from 1990 to 1998 and will be not analyzed in this paper.

RIO CORDON

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 (> 20 mm) from water and fine sediments (LENZI *et alii*, 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. 2). 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 alii*, 1999, 2004). Suspended sediment is measured by two turbidimeters: a Partech SDM-10 light absorption and a Hach SS6 light-scatter instrument. Flow samples are gathered automatically using a Sigma pumping sampler installed at a fixed position in the inlet channel.

Overall, 24 bedload events characterized by bed load transport (grain size greater than 20 mm) were recorded by the Rio Cordon station from 1986 to 2006 (LENZI *et alii*, 2004; MAO *et alii*, 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 alii*, 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 (Fig. 3). 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 – the bed armour layer was removed – and channel banks, plus some point sources

Fig. 3. Images of the Torrent Moscardo taken at the peak of a debris-flow occurred on July 8, 1996 (on the left, from Marchi et al., 2002) and of the Rio Cordon taken at the peak of the bedload event occurred on September 14, 1994 (on the right)

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 alii*, 2004). Comparing the bedload/flow rate relationship and the ratio between bedload volume and effective runoff for the whole floods, Lenzi *et alii* (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 alii* (2004) for a more detailed description of bedload intensities for different durations and recurrence intervals floods..

MAGNITUDE–DISCHARGE RELATIONSHIP

Debris flow magnitudes from the Moscardo and bedload volumes from the Rio Cordon are plotted in Figure 4 versus the associated peak discharges. Both sediment volumes and water discharges have been normalized by the basin areas of the respective study sites (Mao *et alii*, 2009). Despite some differences in measured variables (peak discharge refers to the solid-liquid mixture in the Moscardo and only to the liquid fraction in the Cordon), a certain continuity is apparent between the two channels, even though the lack of overlap preclude any reliable assertion. Assuming a power relationship between event magnitude and peak discharge ($M = aQ_p^b$), The coefficients and exponents are a=356.7 and b=0.85 for the Moscardo and a=0.94 and b=2.8 for the Rio Cordon. The coefficients of determination (R^2) are 0.82 and 0.59, respectively. The exponent of the regression is higher for the bedload events in the Rio Cordon than for the debris flow events in the Moscardo. This suggests a much higher rate of increase of mobilized sediment volumes with discharge for bedload streams than for debris flow channels. In fact, unlimited sediment supply conditions characterize the Moscardo Torrent, where debris flow events are not limited by a lack of available sediment. In contrast, in the Rio Cordon there is a low correlation coefficient of the flood peak and magnitude regression. This is due to the reduced sediment supply in the Rio Cordon, due to the presence of a low-gradient belt in the median part of the basin which reduces the connection between the upper and the lower part of the catchment area. Also, a certain control on the availability of sediments in the Rio Cordon has been exerted by the exceptional September 1994 flood (Lenzi *et alii*, 2004). Figure 4 confirms the much higher efficiency of debris flows in sediment transport compared to bedload movement. In fact, in the Rio Cordon only the September 1994 event reaches a magnitude comparable to those of the smallest debris flows registered in the Moscardo Torrent (around 1000 m^3). At its very peak, the September 1994 flood likely approached hyper-concentrated flow conditions, as inferred by observing the taped documentation of the event.

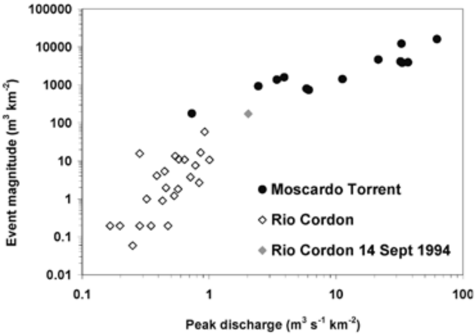

Fig. 4 - Relationship between peak discharge, debris flow magnitude (Moscardo Torrent) and bedload volumes (Rio Cordon)

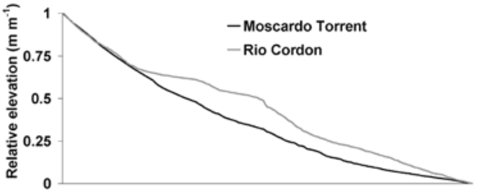

Fig. 5. - Dimensionless longitudinal profiles of the Moscardo Torrent and Rio Cordon. The discontinuity in the middle of the Rio Cordon profile correspond to a geological knick point

.CONTRASTS IN CHANNEL MORPHOLOGY

Sediment supply conditions differ considerably between the two study basins, with sediment availability in the Moscardo Torrent being higher than in the Rio Cordon. As a consequence, the two main channels feature a different degree of bed structuring. In fact, the Rio Cordon displays fairly long step pool sequences (Figure 1, Lenzi, 2001; Trevisani *et alii*, 2010). Step pool morphology usually forms through selective transport and armouring processes under high discharges and low sediment supply (Chin & Wohl, 2005), and in presence of high jamming ratios, i.e., larger clast size/channel width (Church & Zimmermann, 2007). Most importantly, step pool morphology is typical of systems which are supply-limited in terms of sediments (Montgomery & Buffington, 1997). Conversely, the Moscardo Torrent is characterized by a poorly-structured bed profile – only in part modified by the check dams built in its middle segment – dominated by cascade morphology (Figure 1; Mao *et alii*, 2009). Such a bed morphology, typical of steep coarse-bed streams, derives from the frequent disturbances induced by the passage of debris flows which leave lag deposits composed of large particles, and by the lack of sufficiently strong and persisting flows carrying small sediment fractions which would be needed to arrange these clasts under a regular pattern, such as in step pool architecture.

CONTRASTS IN SEDIMENT AVAILABILITY

Contributing area and slope gradient for each cell of the main channels were derived from a 5 m DEM grid by the D8 single flow accumulation algorithm and the steepest descent algorithm (Tarboton, 1997). Longitudinal profiles of the Moscardo Torrent and Rio Cordon main channels were extracted automatically from the DEMs, and are showed in Figure 5. The Moscardo Torrent has a steeper and more linear longitudinal profile than in the Rio Cordon (Mao et al., 2009). The average slope of the main channel is about 37%, but the upper portion is much steeper (>50%) and relatively regular. Conversely, the pattern of the Rio Cordon's longitudinal profile is more complex, and its analysis allows the link between channel morphology and domains of geomorphic processes to be explored. In the upper part of the basin the channel is colluvial, very steep (36%) and exhibits cascade morphology. The channel than flattens within a wide "hanging valley", upstream of a 30 m-high waterfall located in the middle portion of the profile. In the lower-gradient reach upstream of the waterfall, transport capacity decreases thus leading to temporary sediment deposition. Further downstream the channel slope significantly decreases and small tributary channels convey a significant amount of sediments to the main channel, in the form of relatively small debris and mud flows originating from shallow landslides (Lenzi *et alii*, 2004). Finally, in the last 1000 m upstream of the measuring station, Rio Cordon has a mean slope of about 14% and the morphology is characterized by the alternation of step pool and steep cascade reaches, which reflects overall high transport capacity but supply-limited conditions.

MAGNITUDE-RUNOFF REALTIONSHIP

Sediment transport measured at the Rio Cordon station has been compared with Rickenmann's (2001) bedload formula, which has been developed for channel slopes up to 0.2 m m^{-1}, and relates the total bedload volume (M, in m^3, with pore spaces) to the effective runoff volume of the hydrograph (V_{re}, in m^3) and the slope (S) as $M = 1.95\ V_{re}\ S^{1.5}$. For the Rio Cordon the effective runoff has been calculated as the water runoff volume above the threshold discharge for bed load on each flood hydrograph (Lenzi *et alii*, 2004). Figure 6 shows that the bedload magnitude is reasonably predicted only for the 14 September 1994 flood. The considerable overestimation of bedload transported by ordinary floods is mainly due to the sediment supply limited conditions. Also, because of the high channel gradient (> 0.05 m m^{-1}) and the presence of step-pools, the overprediction of bedload transport is likely due to the additional form resistance (provided by immobile boulders and step-pool sequences) as suggested by Ferguson (2007) and previously discussed by Rickenmann (2001) and Rickenmann & Koschni (2010). As to the Moscardo Torrent, Figure 6 clearly shows that the magnitude of transported sediments is substantial higher than in the Rio Cordon. Due to the lack of direct measurements of the water content in the debris flow mixture, in this case the effective runoff has been calculated using the rainfall data collected within the basin. Only the precipitation occurred during the rainfall event that triggered the debris flow was used. Even if this effective runoff value may not be straightforwardly compared with what used by Rickenmann & Koschni (2010) in their analysis of debris flow occurred in Swiss Alps in 2005, it is worth noticing that their debris flow formula ($M = 16378\ A^{1.35}\ S^{1.7}$) is in fair agreement with the volumes measured at the Moscardo Torrent station. The maximum estimated magnitude calculated using channel slope (S) and basin area (A) was not achieved during all debris flow events, most likely due to the occurrence period (Mao *et alii*, 2009). Debris flows in the Moscardo Torrent take place in the summer months. Although total precipitation in autumn is often very abundant, no debris flows have occurred in October and November since the torrent was instrumented. This could be due to the infrequent occurrence of high-intensity storms during these months. Although large amounts of loose debris are present on the slopes of the Moscardo basin, the lack of debris flows in autumn can be also attributed to the temporary paucity of sediments in the initiation zones after the occurrence of summer debris flows.

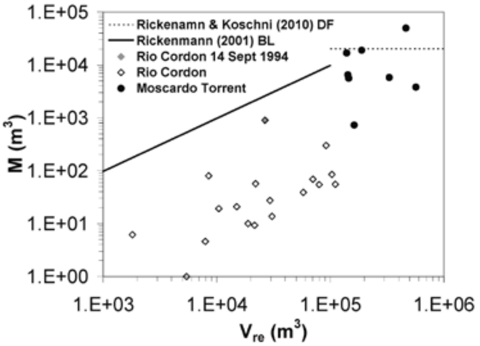

Fig. 6 - Relationship between the magnitude of bedload and debris flow events and effective runoff. The Rickenmann & Koshni (2010) bedload and the Rickenmann (2010) debris flow equations are plotted as well.

CONCLUDING REMARKS

The quantitative comparison of sediment volumes transported in the Moscardo Torrent and in the Rio Cordon made it possible to outline several aspects of sediment dynamics in two small Alpine basins of comparable size and climate, but with highly contrasting characteristics in terms of physiographic setting and sediment supply. The magnitude-frequency relations can be deemed representative of bedload channels with low to moderate sediment supply (Rio Cordon) and of debris-flow torrents with unlimited sediment availability (Moscardo Torrent). As it could be expected, the latter displays much higher magnitudes for comparable peak discharge. The difference in sediment supply conditions and sediment transport behaviour between the two study basins is reflected in the morphological diversity of the channels. The Rio Cordon channel has lower average slope than the Moscardo Torrent and displays an alternation of high-gradient and low-gradient stretches (at both the morphological unit and reach scales). This stepped profile favours partial sediment deposition, so that debris flows could happen (for very infrequent flood events) only in some stretches of the channel and the headwater portion of the basin provide a minor contribution to the annual sediments yield. By contrast, although deposition of small debris flows within the basin has been observed in the Moscardo Torrent, a high channel gradient and a regular longitudinal profile, only slightly modified by the check dams built in the middle part of the channel, make it possible for most debris flows to reach the alluvial fan.

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