MONITORAGGIO, MODELLAZIONE E GESTIONE SOSTENIBILE DEI PROCESSI EROSIVI NEI TERRITORI AGRICOLI, COLLINARI E MONTANI

Il contributo del settore delle Sistemazioni idraulico-forestali

a cura di

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In copertina:

Alto corso del fiume Sele. L'effetto stabilizzante della traversa a monte dell'abitato di Caposele (AV) è reso manifesto dalla formazione di un'isola di vegetazione forestale al centro della colmata a tergo dell'opera.

(foto di S. Puglisi, 15 giugno 2013)

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MONITORING AND ANALYSIS OF THE SEDIMENT TRANSPORT EVENT OF NOVEMBER 2012 IN THE RIO CORDON STATION

Monitoraggio ed analisi dell'evento con trasporto solido avvenuto nel Novembre 2012 presso il bacino attrezzato del Rio Cordon

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Summary

In the analysis of high gradient mountain streams an important aspect is represented by the quantification of the bedload transport. Field data necessary to test transport models and better understand sediment transport phenomena result scarce and difficult to obtain. In the present study, we focus the attention on the results obtained by multiple field surveys carried out after the November 2012 event when bedload transport along the Rio Cordon, a small step-pool channel in the eastern Italian Alps, was generated. The stream is characterized by the presence of a station, managed by the Regional Land Safety Department of ARPAV (Regional Agency for Environmental Protection and Prevention of Veneto), for monitoring water and sediment fluxes since 1986. The measuring station consists of an inclined frame that separates fine from coarse sediments (D>20 mm), which are continuously assessed by a series of ultrasonic sensors fitted above a storage area. After the November 2012 event, a series of field surveys were carried out to identify the source area of the mobilized sediment. The quantification of bedload and fine loads using a Terrestrial Laser Scanner device was then performed, allowing the definition of the volume and grain-size characteristics of the transported sediment. The results have shown that the main source area was represented by lateral small debris flow located just upstream the measuring station. Thanks to the grain-size characterization and the field recognition it was possible to confirm that no morphological changes of the main channel have occurred upstream the sediment sources immission. Therefore, the input of sediment for the stream derives only from lateral debris flow process located near to the catchment output.

Sommario

Nello studio dei torrenti montani un importante aspetto è rappresentato dalla

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quantificazione del trasporto solido di fondo. In questo ambito dati reali, ricavati direttamente da rilievi di campo e utili per testare i modelli oltreché per migliorare la conoscenza del fenomeno, risultano scarsi e di difficile acquisizione. Nel presente studio si presentano i risultati ottenuti da rilievi di campo effettuati successivamente all'evento caratterizzato da trasporto solido di fondo avvenuto nel Novembre 2012, presso il Rio Cordon. Questo è un piccolo collettore montano situato nelle Alpi Orientali e caratterizzato da prevalente morfologia a step-pool. All'interno del suo bacino è presente una stazione sperimentale, gestita dall'ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto) ed in particolare dal Dipartimento Regionale per la Sicurezza del Territorio, che permette il monitoraggio dei deflussi idrici e solidi dal 1986. La stazione consiste in un canale d'imbocco asimmetrico e di una griglia inclinata che separa il materiale fine da quello grossolano (D>20 mm), il quale è continuamente misurato tramite una serie di sensori ad ultrasuoni posizionati al di sopra della piazza di deposito. Successivamente all'evento del Novembre 2012, sono stati effettuati una serie di rilievi di campo con l'obiettivo di identificare l'area sorgente da cui il materiale si è mobilizzato. La quantificazione del materiale fine e di quello grossolano è stata effettuata tramite l'impiego di un sensore Terrestrial Laser Scanner, permettendo così la definizione del volume oltreché delle caratteristiche granulometriche del materiale trasportato. I risultati ottenuti hanno mostrato come la principale area sorgente sia stata una piccola colata detritica verificatasi appena al di sopra della stazione di monitoraggio. Grazie alla caratterizzazione granulometrica ed ai rilievi in campo, è stato possibile affermare che nessuna variazione geomorfica è avvenuta nel collettore principale, a monte dell'area sorgente. Pertanto i sedimenti trasportati sono stati originati solamente dalla colata detritica laterale, localizzata in prossimità della sezione di chiusura del bacino.

1. Introduction

In small Alpine catchments the transport processes are influenced by various factors such as: stream hydrodynamics, grain size distribution of transported and bed material, channel morphology and slope erosion phenomena (Lenzi et al., 1999). Moreover, especially in the Alpine environment the heterogeneity in typology, extension and position of sediment source areas causes a large variability in the effectiveness of transport processes (Cavalli et al., 2013). In this context, such processes may occur mainly as floods with suspended and bedload transport but also as debris and mud flows, depending on the geomorphological and sediment supply conditions (Fattorelli et al., 1988; Church 1998; Billi et al., 1998; Lenzi, 2000; Bathurst, 2003; Lenzi and Marchi, 2000; Lenzi et al., 2003, 2004; Mao et al., 2006, 2009, 2010). The suspended transport in mountain streams is commonly considered to be of secondary importance with respect to the just mentioned phenomena (Lenzi et al., 2003). Despite this, suspended load may exceed bedload, particularly in unstable channels (Barsch et al., 1994), as well as it can significantly affect aspects such as channel morphology, water quality, and availability of aquatic habitat (Wohl, 2000). The analysis of suspended sediment transport that occurs during a flood event, in particular the relationship between the suspended sediment concentration (S.S.C.) and the water discharge, combined with the lag between the peak of S.S.C. and the peak of discharge, can allow to acquire some interesting indications about the localization of the source areas. In this sense, Kurashige (1996), conducting a research on headwater streams in Japan, indicates that S.S.C. may reach maximum values before or during flood peaks, depending on whether sediment comes primarily from the channel bed or from the hillslopes. This type of research was also carried out in the Rio Cordon, an Alpine instrumented catchment (Lenzi, 2000; Lenzi and Marchi, 2000), in particular analyzing the hysteresis loops resulting from the relationship between S.S.C. and water discharge, for specific events. These, in turn, have been associated to different types and locations of the active sediment sources. The suspended sediment transport plays also a key role in mountain streams concerning the total sediment load. Some researches considering this topic and carried out in the Rio Cordon have shown that 76% of the total sediment load occurred in this study area, between 1986 and 2001, was in the form of suspended transport (Lenzi et al., 2003). On the other hand, the analysis and the quantification of the bedload transport, in the Alpine environment, is of fundamental importance for hazard assessment, understanding of the morphodynamics of higher order channels, planning and design the reservoir sedimentation (Rickenmann, 1999; Andreoli et al., 2005; Nitsche et al., 2011; Yager et al., 2012;) and furthermore the bedload volumes represent the primary source of concern, more than flood water volumes (Lenzi et al., 2004). The importance of this phenomenon contrasts with the fact that its monitoring, especially in a small (Area < 10 km^2) steep mountain basins, is problematic due to their high-energy and impulsive nature. In this context appears necessary, for a correct assessment, the implementation of a robust and reliable system for performing direct field observations (Mao et al., 2009). In this sense, the monitoring activities carried out by permanently installed devices fully meet all these requirements, nevertheless they feature very high costs. For these reasons the existing experimental sites represent precious tools for the scientific community as well as for the institutions that deal with mountain streams and land use planning (Di Stefano et al., 2007). In particular, these monitoring sites become of extreme value when long-term series of data are eventually produced, thus allowing statistical analysis and experience-based predictions (Mao et al., 2006). That is the case of the Rio Cordon experimental station, where this research took place with the aim of analyzing the most recent sediment transport events, occurred in November 2012.

2. Materials and methods

2.1 Study basin

The Rio Cordon basin is located in the North-Eastern of Italy, in the locality of Selva di Cadore (BL) and it originates at an altitude of 2763 m a.s.l., extending over a surface of about 5 km^2. The catchment is characterized by typical Alpine climatic conditions, with average annual values of precipitation of about 1100 mm occurring mainly as snowfall from November to April, and as storms in summer season. These climatic conditions, in turn, affect the runoff that is dominated by snowmelt in May and June, with summer and early autumn that feature important runoff events. The geology mainly consists of dolomites, limestones volcaniclastic conglomerates, tuff sandstones (Wengen group) with widespread quaternary deposits. In this catchment the forests cover just the 7% of the total basin (*Picea abies* and *Larix decidua*) and, specifically, only in the lower part of the area. The major part of the catchment features Alpine grasslands (61%) and shrubs (18%). The remaining 14% of the basin extension is characterized by bare land. No urbanized area and even roads are present within the catchment. Field surveys, which took place after the major floods of September 1994, estimated that the source areas covered the 5.2% of the total basin and appeared especially as talus slopes, shallow landslides, eroded stream banks and debris flow channels (Lenzi et al., 2003), some of these located just upstream of the monitoring station. In this sense, a peculiarity of this catchment is that about 50% of the total sediment source area is located upstream of a median, low gradient belt where sediment deposition takes place. As a consequence of this characteristic, the basin headwaters provide a minor contribution to the total sediment yield, independently from the local intensity of erosion processes (Dalla Fontana and Marchi, 2003). In this context, Rio Cordon flows for 2.8 km characterized by a boulder-bed, and by a step-pool morphology that gives a high stability to the bed channel for floods events with recurrence intervals (R.I.) lower than 30-40 years (Lenzi, 2001). The analyses carried out on the grain size distribution estimated that D_{16} is equal to 37 mm, while D_{50}=119 mm and D_{84}=357 mm (Lenzi et al., 2004). Moreover, the investigation highlighted as the subsurface grain size distribution is finer than at the surface (D_{50ss}= 38 mm and D_{84ss}= 125 mm), demonstrating a strong degree of surface armouring (D_{50}/ D_{50ss} ~ 3) (Mao et al., 2010).

2.2 The Rio Cordon measuring station

In this basin, at an altitude of 1763 m a.s.l., just below the upper limit of the forest, was build in the 1986 a station for monitoring water discharge, suspended sediment and bedload transport. The structure (Fig. 1) consisting of an inlet flume where the flows are channeled, an inclined grid that separates the coarse sediment that is deposited into a storage area, an outlet flume and a settling basin (area of about 205 m^2 and depth of 3.5 m) where is stored the sediment finer than 20 mm. The monitoring station is actually managed by the Regional Land Safety Department of ARPAV.

The structure is also equipped with a meteorological station that allow the acquisition of data concerning precipitation, air temperature, atmospheric pressure, relative humidity and solar radiation. Another ARPAV meteorological station, with air temperature sensors and rain gauges, is located upstream, at an altitude of 2130 m a.s.l, in the locality of Mondeval di Sora (BL). Within the monitoring station, the liquid discharge is continuously measured (1 hr intervals, 5 min during floods), from March to November, through 2 water level gauges and 1 sharp-crested weir, installed at 3 different locations. As already said, the measurement of bedload is acquired by an inclined grid that separates the

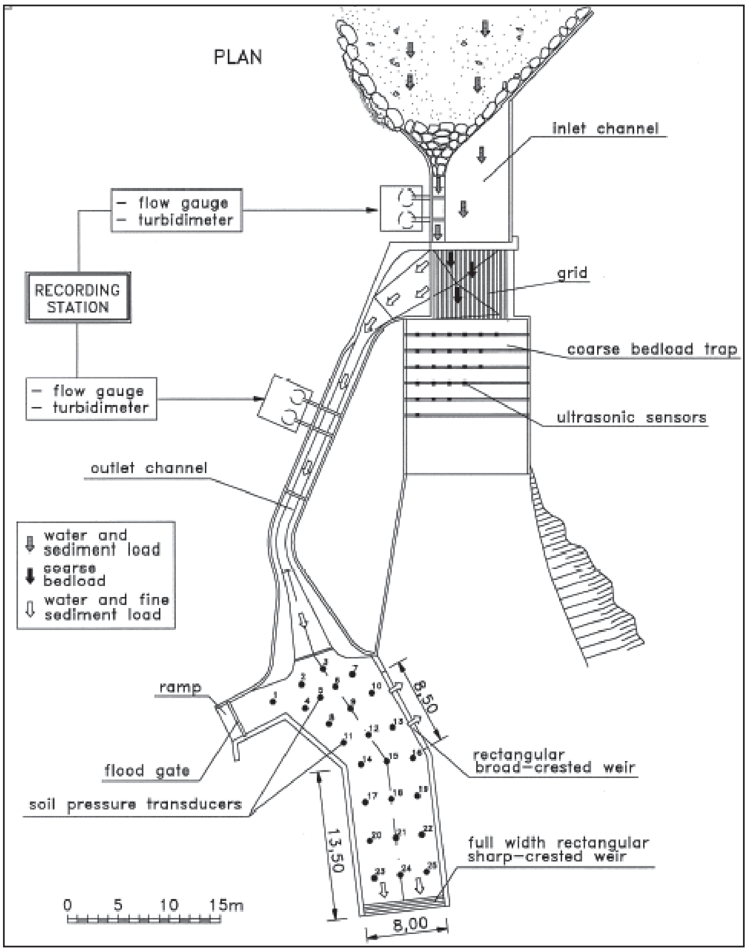

Fig. 1 - *Plan of the Rio Cordon monitoring station (after Lenzi et al., 2004)*

coarse sediment (minimum size > 20 mm) from the water and the fine sediment. After the partitioning, the bedload slides over the grid and accumulates in a storage area where its volume is measured, every 5 minutes, by 24 ultrasonic sensors placed on a fixed frame, in this way the sensors can continuously survey the growing of volume. The transported sediments finer than 20 mm are measured by 25 pressure transducers cells able to measure the pressure of the material deposited in a settling basin located downstream of the outlet flume (Mao et al., 2010). The suspended sediment is measured by two turbidimeters: one is a light absorption device (model Partech SDM-10) installed in the outlet channel; while the other is a light scattered instrument (Hach SS6), fitted in the 1994 in the inlet channel. Moreover, when the discharge exceeds a specified threshold, flow samples are gathered automatically using a Sigma pumping sampler, placed along the inlet flume (Lenzi and Marchi, 2000). All the collected data, in this way, are daily radio transmitted to the Arabba Avalanche Centre of ARPAV. A complete and detailed description of the measuring station is also available in several previous papers (Fattorelli et al., 1988; Lenzi et al., 1999; Lenzi et al., 2004; Picco et al., 2012a, 2012b), where the facilities for monitoring water discharge, suspended sediment and bedload transport have been described in detail. The presence of the monitoring station enabled to analyze every flood events, characterized by bedload and suspended sediment transport, occurred from 1986 to the present.

In table 1 the main characteristics of the floods recorded, including the last event of the November 2012 are shown.

All these floods are also described in detail in numerous previous papers (Lenzi et al., 1999; Lenzi, 2000, 2001; Lenzi and Marchi, 2000; Picco et al., 2012a, 2012b). Special attention must be given to the September 1994 flood, the most important event occurred during the study period, that caused a significant alteration of the channel geometry (Lenzi, 2001) as well as in the sediment supply characteristics of the basin (Lenzi et al., 2004). The flood was originated by high intensity rainfall characterized by maximum rainfall rates of 7.2 mm for 5 min, 16.4 mm for 15 min and 25.3 mm for 30 min (Lenzi and Marchi, 2000) which caused the highest discharge ever recorded by the Rio Cordon measuring station, with a value of 10.4 m^3/s and a recurrence interval of about 50 years.

	Qp (m^3 s^{-1})	RI (years)	BL (m^3)	T_{BL} (h)	Re (10^3 m^3)	BLr (m^3 h^{-1})	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
11 October 1987	5.15	5.6	54.8	8.00	79.9	6.9	—	—	—
15 July 1988	2.43	1.6	1.0	1.00	—	—	—	—	—
3 July 1989	4.39	3.9	85.0	27.00	103.4	3.1	54	103	207
22 May 1990	0.85	1.0	1.0	1.00	—	—	—	—	—
17 June 1991	4.00	3.3	39.0	20.00	57.9	2.0	30	51	100
5 October 1992	2.91	2.0	9.3	10.00	21.5	0.9	22	43	111
2 October 1993	4.28	3.7	13.7	6.00	30.7	2.3	29	61	135
18 May 1994	1.79	1.2	1.0	12.00	5.4	0.1	21	33	52
14 September 1994	10.42	52.6	900.0	4.00	26.6	225.0	65	116	226
13 August 1995	2.72	1.8	6.2	1.00	1.8	6.2	—	—	—
16 October 1996	2.96	2.0	57.0	15.00	22.0	3.8	40	79	143
27 June 1997	1.46	1.1	1.0	1.00	—	—	—	—	—
7 October 1998	4.73	4.6	300.0	17.00	91.8	17.6	40	78	157
20 September 1999	3.65	2.8	19.2	6.40	10.4	3.0	32	54	98
13 October 2000	3.28	2.3	55.6	35.00	110.6	1.6	39	61	111
11 May 2001	1.46	1.1	80.0	13.00	8.5	6.2	33	48	69
20 July 2001	1.98	1.4	20.9	4.70	15.0	4.4	—	—	—
May 2002	2.29	1.5	27.4	20.00	29.4	1.4	39	59	99
16 November 2002	2.35	1.5	10.0	14.50	18.9	0.7	—	—	—
27 November 2002	2.77	1.9	69.1	30.00	70.3	2.3	26	44	78
03 May 2003	1.02	1.0	1.0	1.00	—	—	—	—	—
12 June 2004	2.22	1.5	4.6	—	—	—	25	38	62
6 October 2005	1.68	1.2	0.9	—	—	—	18	30	55
19 May 2006	1.28	1.0	0.7	—	—	—	—	—	—
11 November 2012	2.10	1.4	14.2	1.35	44.8	9.0	23	38	70

Table 1 - *Characteristics of the floods recorded by the Rio Cordon monitoring station, since 1986*

This discharge caused the destruction of the bed armour layer formed over years, and as a consequence, the channel bed became the main source of sediment, creating unlimited sediment supply conditions. In addition to that many old sediment sources were reactivated and new ones were formed, due to the high discharge (Lenzi et al., 2004). Specifically, thanks to the field surveys conducted immediately after the event, several minor bank erosion and bank failures were observed, both along the main channel and along some tributaries (Billi et al., 1998). This large quantity of sediment, in particular fine and medium size, stored in the stream network was easily removed and transported downstream by subsequent ordinary floods. In fact, previous researches (Lenzi et al., 2004; Mao et al., 2010), regarding the bedload intensity of each flood event registered, highlighted how, for the pre-1994 period, the average bedload rates were 0.27 kg s^{-1}, while this value increases to 2.06 kg s^{-1} in the post-1994 episodes. The same trend is observable when analyzing the mean annual sediment yield (Lenzi et al., 2003): in the period 1986-1993 this values reaches 77.7 t km^{-2} $year^{-1}$, while in the period 1995-2001, after the 1994 flood, the value increases to 130.6 t km^{-2} $year^{-1}$. Therefore the September 1994 flood represents clearly a moment of considerable change for the channel, particularly for its morphology as well as the sediment availability (Mao et al., 2010). From a morphological point of view, the high discharge has heavily altered the step-pool morphology that characterized the Rio Cordon. The typical sequence of step and pool was restored only after several ordinary floods, through a slow action of pool scouring, supported by supply-limited conditions along the stream network (Lenzi, 2001). Another significant flood recorded by Rio Cordon measuring station, was the event of the 11th of May 2001. In this case, a quasi-unlimited sediment supply condition took place as a consequence of a mud flow occurred during snowmelt, in fact the soil saturation mobilized a shallow landslides that then moving along a small tributary (Lenzi et al., 2004). As a consequence of this, a debris fan (4176 m^3) formed on the Rio Cordon main stream, providing fine sediment easily transportable downstream to the main channel. These particular conditions allowed, in occasion of an ordinary flood event (snowmelt flood), the transport to the station of about 80 m^3 of bedload volume.

2.3 November 2012 bedload event

The functioning of the various sensors installed within the Rio Cordon station allowed us to analyze the event that took place in November 2012. Specifically, there were two subsequent floods, on the 5th and 11th of November. The records of water discharge were slightly different among the 3 sensors installed within the monitoring station, for this reason for the analysis we used the sensor placed in the inlet flume, coherently with the previous analyses. In detail the event of the 5th of November was characterized by a peak water discharge of 1.8 m^3s^{-1}, while during the 11th November flood the peak reached 2.1 m^3s^{-1}; however similar to the estimated bankfull discharge equal to 2.3 m^3s^{-1} (Lenzi et al., 2006). From the hydrograph of the two subsequent floods (Fig. 2), we can be observed how duration and shape are quite similar.

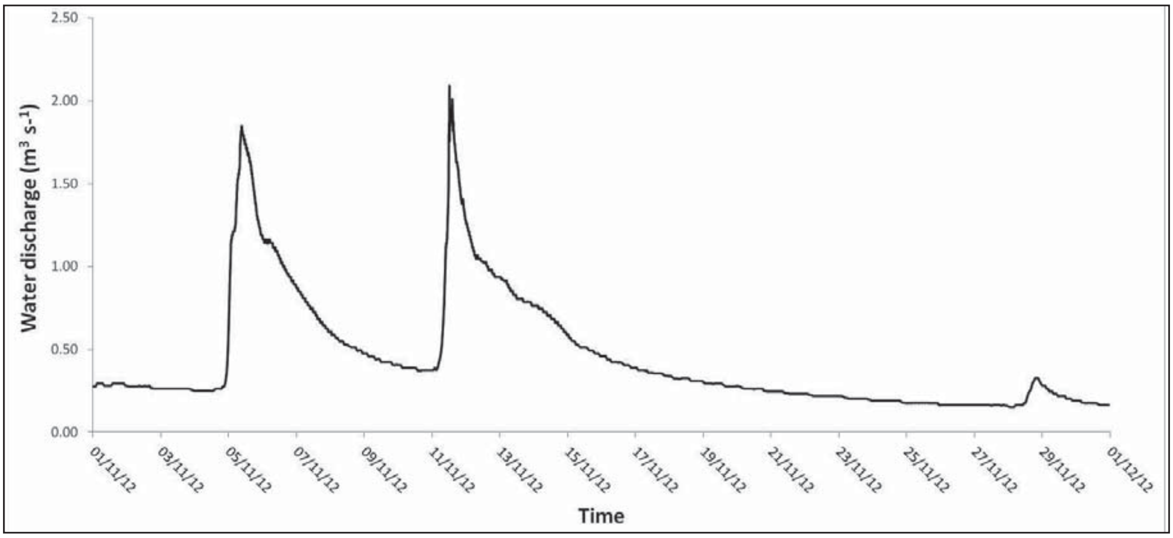

Fig. 2 - *Hydrograph for the month of November 2012, measured by Rio Cordon station*

In addition, the discharge caused a deposition of coarse sediment in the storage area, highlighting the occurrence of bedload transport. This phenomenon is confirmed also from the sensors installed in the monitoring station. About 10 days after the bedload event, a series of field surveys were carried out in order to quantify the volume of the coarse material deposited in the storage area, evaluate the grain size distribution and identify the source area of the mobilized sediment. The volume of the deposited sediment was acquired by a Terrestrial Laser Scanner survey, using a Leica ScanStation2 device, able to measure up to 50000 point per second. The volumetric value was calculated by a difference between the Digital Elevation Model (DEM) of the bedload volume deposited, and the DEM of the empty storage area. This assessment is also particularly accurate thanks to high resolution of the compared digital elevation models, characterized by a cell size of 0.02x0.02 m. This degree of resolution was achievable thanks to the large amount of points detectable by the TLS survey. The grain size distribution of the bedload material contained in the storage area was carried out through a manual grid by number method, using an interdistance of 0.60 m, or rather equal to 2 D_{max} (D_{max}= 0.30 m). Regarding the source area, the first field evidences identified a debris flow channel located just upstream of the monitoring station (Fig. 3) as the main source. As said before, this type of channel is a typical source area that provides sediment easily transportable downstream, in fact as observed, along the banks there were clear signals of the occurrence of a small debris flow (Fig. 4). At the same time no changes on the main channel of the Rio Cordon were identified, upstream this point of sediment immision.

3. Results and discussion

Although the hydrograph are quite similar concerning duration and shape, the sediment transport is fundamentally different among the two floods. The ultrasonic sensors showed that there was no bedload transport during the first

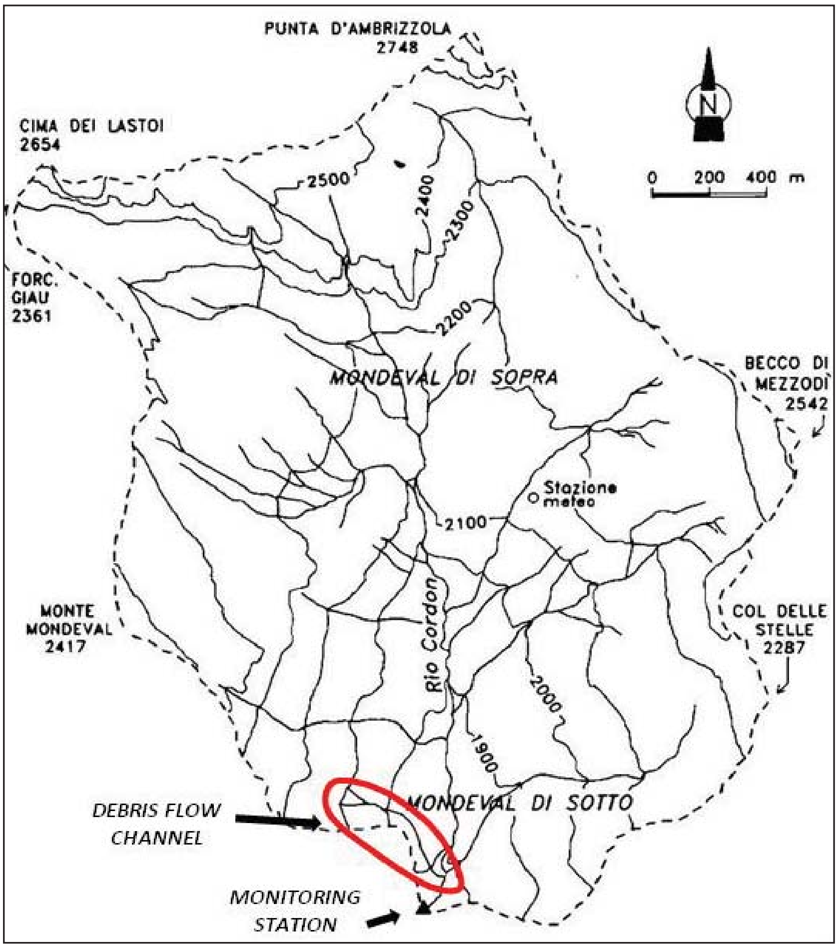

Fig. 3 - *Rio Cordon basin map with lateral debris flow channel localization in the red circle*

Fig. 4 - *The debris flow channel, after November 2012 event*

flood. Moreover, suspended sediment transport was very low, peaking around 0.1 g l^{-1} during the flood peak. On the other hand, during the 11th November flood, suspended sediment transport was much higher, peaking a value of 9.9 g l^{-1} and furthermore the sensors registered bedload transport. These different characteristics related to the sediment supply of the two floods, allow us to say that the debris flow has occurred after the 5th of November but before the 11thof

November, or rather in the days between these two dates. During the 11th November event, the ultrasonic sensors estimated a bedload volume of about 18.40 m^3, but there are some fluctuations in the data, probably caused by the wind that shifts these sensors placed above the bedload storage area. For this reason, for subsequent analyses we chose to use only the volume assessed by TLS survey, that corresponds to 14.20 m^3.

Regarding the transport, unfortunately the 5 min ultrasonic sensors data are very scattered and do not allow to calculate an exactly bedload transport rate, however using these data can be said that bedload occurred between 9.00 and 13.25 of the 11th of November. If we take into account the shape of the hydrograph and the shape of the suspended sediment transport data, we could reasonably assume that bedload could have started around 11.50, at a discharge of approximately 1.5 m^3 s^{-1}. This is consistent with data obtained from previous floods. If that is true, bedload would have lasted for 95 min maximum, which would give an averaged value of bedload transport rate of around 9 m^3 h^{-1}. This is clearly an underestimated value and it's likely that maximum transport rate would have been higher. Anyway, this underestimated value is still quite high, considering that during October 1998 (second highest flood after September 1994 event) the bedload rate peaked at 17.6 m^3 h^{-1}. The analysis concerning the grain size distribution have allowed to create the cumulative frequency curve (Fig. 5) relating the transported bedload volume.

This graph shows how about 100% of the transported material is predominantly gravel, especially small cobble and coarse pebble, indeed the 98.6% of the sediment are finer than 128 mm, while the entire range of particle size is comprised between 11.2 mm and 181 mm. It is also interesting to note that the

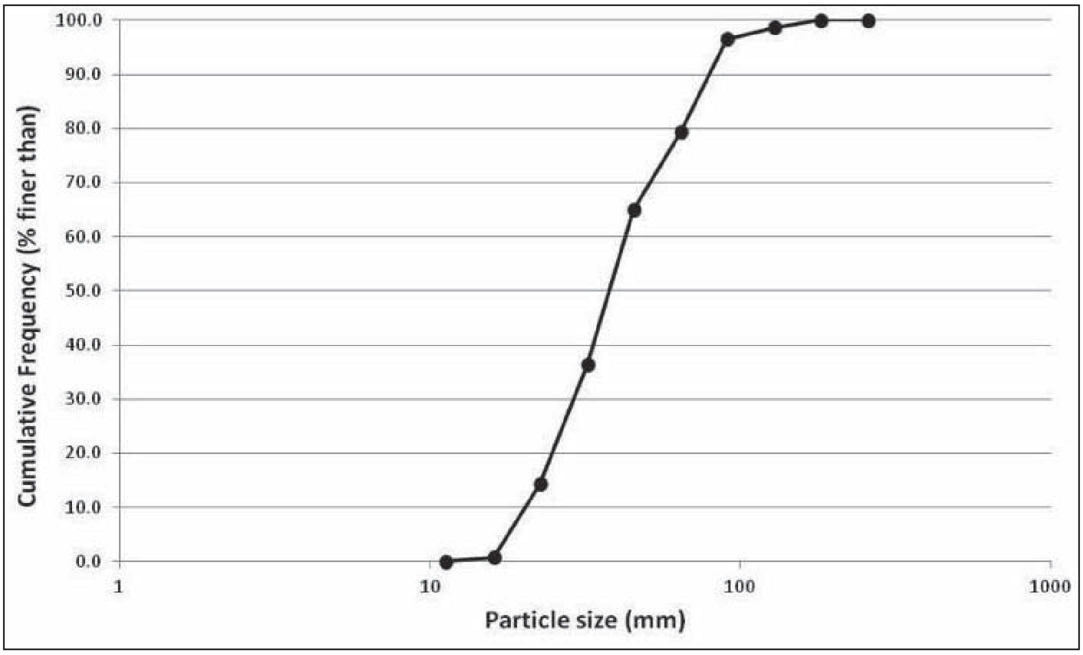

Fig. 5 - *Cumulative frequency curve relating to the bedload volume, transported by the November 2012 flood event*

values estimated for D_{16} (23.2 mm), D_{50} (37.7 mm) and D_{84} (70.4 mm) are among the lowest ever reported, considering the 25 events investigated in the Rio Cordon (Table 1).

3.1 Temporal trends in the bedload transport

The availability of the coarse volume transported and the hydrograph, for the 11th November 2012 flood, allowed the calculation of the ratio between bedload volume (BL) and effective runoff (Re). The effective runoff is defined as the portion of the hydrograph volume that has contributed to the bedload transport, between the beginning to the end of the transport. The determination of the BL/Re ratio allows to infer a temporal trend in the bedload yields and, in this case, permitting to compare the bedload events that occurred in the last 27 years. In figure 6 is shown the BL/Re ratio calculated for each flood that took place in the Rio Cordon basin, including the event of November 2012.

The BL/Re ratio shows an initial decreasing trend, caused by the limited supply conditions in the 1986-1993 period. The September 1994 event is characterized by the highest BL/Re ratio (33.83), thanks to the extreme conditions that took place during this flood. Indeed, as said before, the high water discharge caused the disruption of the streambed armor layer and, at the same time, the

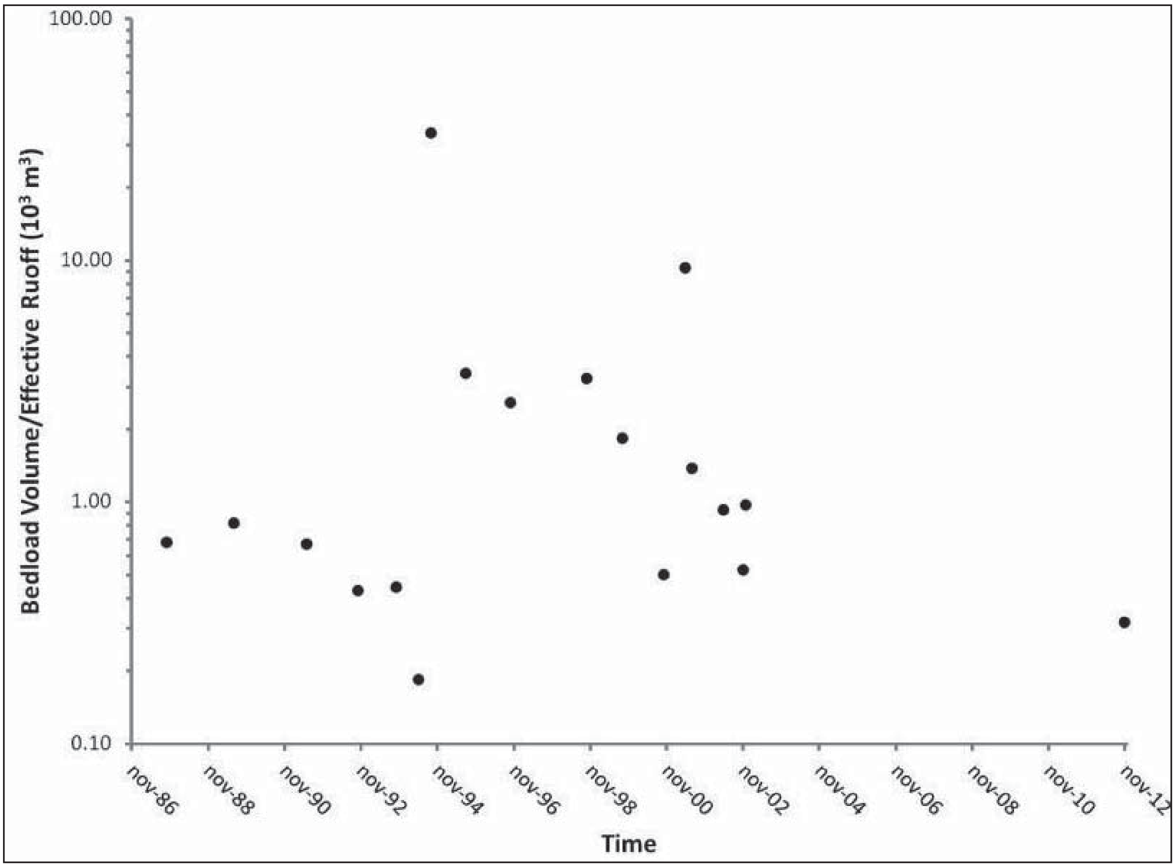

Fig. 6 - *The ratio between bedload volume (BL) and effective runoff (Re) calculated for each flood event that occurred since 1986*

reactivation of many old sediment sources and the formation of new ones, determining unlimited sediment supply conditions. In the period following September 1994 flood there is a new decreasing trend, with events initially characterized by higher values of BL/Re ratio than the 1986-1993 period. This is due to the large amount of sediment eroded from the hillslopes and stored in the stream network, by the 1994 event, and then easily transported downstream by the subsequent ordinary floods (Picco et al., 2012a, 2012b). The decreasing trend seems to continue also in the recent period, in fact the BL/Re ratio estimated for the November 2012 flood (0.32) event shows a value very close to those that characterized the 1986-1993 period. This demonstrates as, in the recent period, there is a return to limited sediment supply conditions, due to the progressive depletion in the availability of transportable sediment, due in turn to the progressive streambed armoring and a restored of the step-pool morphology. Thanks to 27 years of data, it can be said that a change in the BL/Re trend can take place only in the case of occurrence of a new extreme event, as the September 1994 flood which reactivated the bed channel as source as well as the inactive areas located on the hillslopes. Punctual changes in the general temporal trends may also be due to the occurrence of slope instability phenomena, especially debris flows and mud flows, that provide as available a large amount of sediment transportable also by a ordinary floods, as happened for the event of May 2001. In this case, the flood is characterized by quasi-unlimited sediment supply conditions and a high BL/Re ratio, but does not create a change in the subsequent general trend.

3.2 Hysteresis relation between S.S.C. and water discharge

Thanks to the continuously monitoring carried out by the experimental station, it was possible to estimated the values of suspended sediment concentration (S.S.C.) that characterized the November 2012 event, and in particular the hysteresis relation given by the relationship between S.S.C. and the water discharge. In this sense, suspended sediment transport hysteresis during 11th November flood (Fig. 7) shows a clockwise loop, suggesting an immediate availability of sediment supply, already during the initial phase of the event. This is consistent with the field evidences and therefore with the interpretation that most of the sediment came from the debris flow channel, which have reached the main stream just few hundred meters upstream the monitoring station. Furthermore, these results are in line with other clockwise hysteresis loops observed in the Rio Cordon for the floods of June 1991, October 1992 and August 1995 (Lenzi and Marchi, 2000). Events where the clockwise trend could be related to sources located in the lower part of the basin, at short distance from the monitoring station. The hysteresis of August 1995 can be referred to the availability of fine sediment coming from the hillslopes and deposited within the stream during the flood of September 1994 (Lenzi and Marchi, 2000). On the other hand, the same authors observed a un-clockwise loop in the Rio Cordon during the event of October 1996 due to the sources located on hillslo-

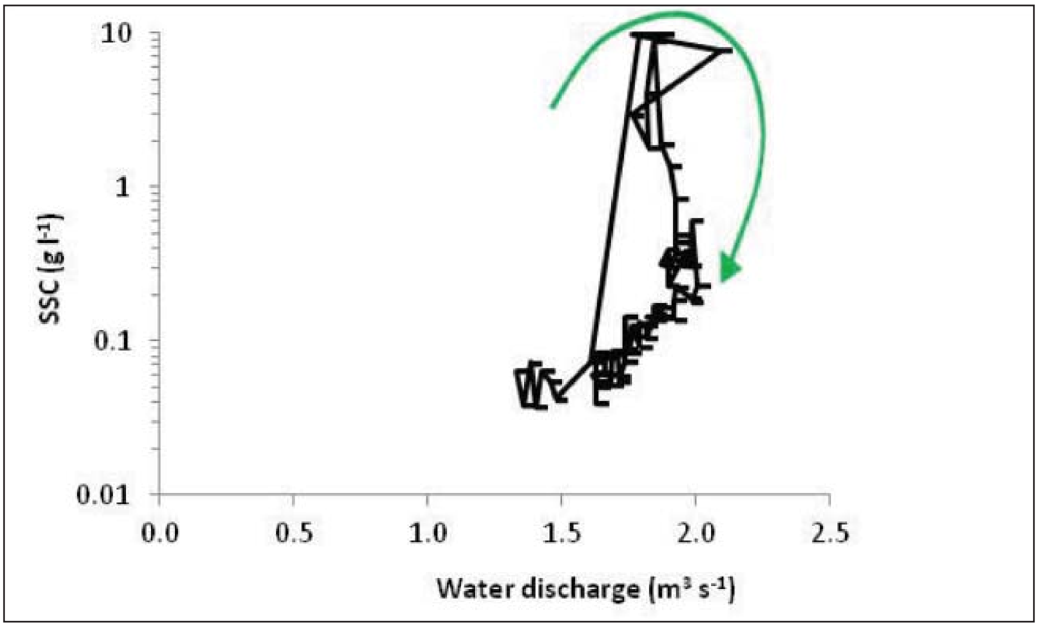

Fig. 7 - *11th November 2012 flood, hysterisis relation between S.S.C. and water discharge*

pes, but at higher distance from the monitoring station. According to these results we can also observe, in the relationship between suspended sediment concentration and water discharge, an abrupt decrease in the S.S.C. values, despite the persistence of significant discharge. This trend was already detected in the past for some floods occurred in the Rio Cordon. Specifically, it was observed in June 1991 and October 1993 events, and it was caused by the wash out of fine lose material originating from the lower part of the basin so from sources characterized by a short travel time to the measuring station (Lenzi and Marchi, 2000).

4. Conclusion

The monitoring station located in the Rio Cordon allowed the analysis of 25 flood events, characterized by bedload and suspended sediment transport, that took place from 1986 to the present. The monitoring devices made possible to the investigation of the most recent event, which occurred in the November 2012. In this case, the occurrence of a small debris flow in the basin made available sediment which was then transported downstream from the ordinary flood of the 11th of November (Q= 2.1 $m^3 s^{-1}$, R.I.= 1.4 years). The bedload volume quantified by the TLS survey, is equal to 14.20 m3. The field evidences and the analysis of the hysteresis relationship between S.S.C. and water discharge, have allowed to clearly identify the source area, from which it was originated the debris flow. In this sense, the source is a debris flow channel located just few hundred meters upstream the monitoring station. These results are consistent also with the temporal trend in the bedload transport, concerning the Rio Cordon floods. Indeed, the integration of the temporal trend with the value of ratio BL/Re regarding the November 2012 event, shows that there is a return to limited sediment supply conditions and, in such circumstances, the debris flow channel represents the main type of source area in the Rio Cordon basin. Under such conditions, the general limited sediment supply may change only due to the occurrence of a new extreme flood, as the September 1994 flood, that removes the streambed armour layer which in the meantime has been restored, and reactivated old source areas now not active. Otherwise, practically unlimited sediment supply conditions can occur only occasionally in the event of debris flows or mud flows that make available a large amount of sediment transportable also by subsequent ordinary floods. In conclusion, we can affirm that the Rio Cordon measuring station has provided 27 years of excellent results concerning the sediment transport in Alpine catchment, and as seen in the present research, continues to provide valuable data.

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