Internationales Symposion
INTERPRAEVENT 2004 – RIVA / TRIENT

IMPACT OF SEDIMENT SUPPLY ON BED LOAD TRANSPORT IN A HIGH-ALTITUDE ALPINE TORRENT

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ABSTRACT

The main purpose of the research is to emphasize the connection between channel processes and sediment sources in mountain basins. The study area is the Rio Cordon basin (northeastern Italian Alps, Belluno, Veneto Region, Italy). This catchment has been instrumented in 1985 to monitor major hydrologic, hydraulic, and morphological parameters. Bed load is measured at a special facility with an inclined grid on which particles larger than 20 mm slide into a storage area. Twenty flood events are analyzed statistically and their relations to channel processes are investigated. Cycles of bed armouring due to "ordinary" events are present along with the occurrence of an high-magnitude, low-frequency event. Limited and unlimited sediment supply conditions and flood hydrograph characteristics are considered, in order to account for large variations of the ratio between bed load volume and effective runoff volume. The analysis demonstrates both the control exerted by sediment availability on bed load transport rates and the persisting long-term impact of major floods on mountain streams.

Key words: Instrumented basin, Italian Alps, Floods, Bed load, Sediment sources, Sediment supply.

INTRODUCTION

Geomorphic processes acting on high altitude and steep catchments have a relevant importance on river processes downstream and thus on fluvial hazard assessment. They are still relatively unknown because of difficulties in carrying out field investigations in such inconvenient locations. Nevertheless, the understanding of the relationships among mountain catchments characteristics, stream morphology and sediment yield is crucial, especially in Alpine regions, where nowadays high-altitude territories are being encroached by human activities all year round, posing a strong need to predict and prevent natural disasters even in once remote areas.

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In mountain basins, bed load volumes represents the primary source of concern, more than flood water volumes themselves. Many investigations have been carried out both analytically and in the laboratory to find out reliable bed load transport equations. However, very few (Meyer-Peter & Muller, 1948; Mitzuyama, 1977; Smart & Jaeggi, 1983; Smart, 1984; Bathurst *et al*., 1987; Rickenmann, 1990; Suszka, 1991) have been developed for steep boulder-bed channels, where roughness conditions, sediment grading and hydraulic phenomena make these streams completely different from lower gradient gravel- or sand-bed ones.

Furthermore, research aiming at validating these bed load formulae with field data has been rather scarce (Johnejack & Megahan, 1991; Blizard, 1994; Rickenmann, 1994, 1997; D'Agostino & Lenzi, 1996, 1999; Lenzi *et al*., 2000) due to the obvious problems of measuring very coarse sediment transport, and occurring only at very high flow rates. In fact, the frequency of bedload movement can be idealized to be function of the ratio hydraulic driving force over channel resisting forces. Poorly sorted mountain rivers may require extreme infrequent discharges for the mobilization of the coarsest clast size, whereas annually only a portion of finer (gravel and cobble) particles is likely to be entrained (Wohl, 2000).

When attempting to calculate the total bed load volume transportable during a flood event, these equations are usually applied to the discrete hydrograph above the estimated initial and final motion threshold discharges. Such a simplification has several flaws, a major one is that it implies the assumption of unlimited availability of sediment to be entrained and transported by the competent flow, not considering the possible presence of strong bed armouring which actually make sediment availability limited, "starving" an otherwise erosive flow rate. Only when the armouring breaks-up during severe, low recurrence floods, finer material becomes available for transport. In fact, most of the formulae typically overpredict bedload rate in the field in some cases by several orders of magnitude (Gomez & Church, 1989; Blizard, 1994).

On the other hand, hillslope and tributary processes as landslides and debris flows may donate characteristics of unlimited or quasi-unlimited conditions to medium intensity, more frequent flood events which otherwise would transport only small amounts of sediment. The degree of coupling between channel and hillslope processes is a key issue in mountain basins, because its variations over the years impart large interannual differences in bedload yield as a result of changes in sediment supply to the channel. Bogen (1995) effectively depicts mountain rivers as a number of *local* erosion and sedimentation subsystems, and therefore records of sediment yield may not characterize the system as a whole.

However, as pointed out by Wohl (2000), in the absence of widely applicable and reliable predictive equations for bedload yield, its assessment can be extrapolated from available records of sediment yields, thus stressing the relevance of measuring facilities providing temporal series of bedload data.

The aim of this paper is to present 17 years of flow and bedload rates recorded at the measuring facility in the Rio Cordon basin (Dolomites, Italian Alps), which have provided 20 flood events that have been analysed statistically in order to estimate return intervals of both water peak discharge and bedload total volumes. The occurrence of two different causes of "unlimited" sediment supply during the recorded period will also allow to analyse their effect on bedload yield of the catchment.

STUDY BASIN AND MEASURING STATION

The research was conducted in the Rio Cordon catchment (Fig. 1), a small water course of the Dolomites (Eastern Italian Alps). The main physiographic characteristic of the instrumented watershed (5 km^2) are reported in Lenzi *et al*. (this volume). The solid geology consists of dolomites, which make up the highest relief in the catchment area, volcaniclastic conglomerates and tuff sandstones (Wengen group). In the lower part of the watershed the Buchenstein group consist of calcareous, calcareous-marly and arenaceous rock outcrops. Quaternary moraine and scree deposits are also very common.

Soils are generally thin and belong to three main families: a) skeletal soils, occurring on steep slopes with a discontinuous vegetation cover; b) organic soils, with more continuous and dense vegetation cover than the previous group; c) brown earth soils.

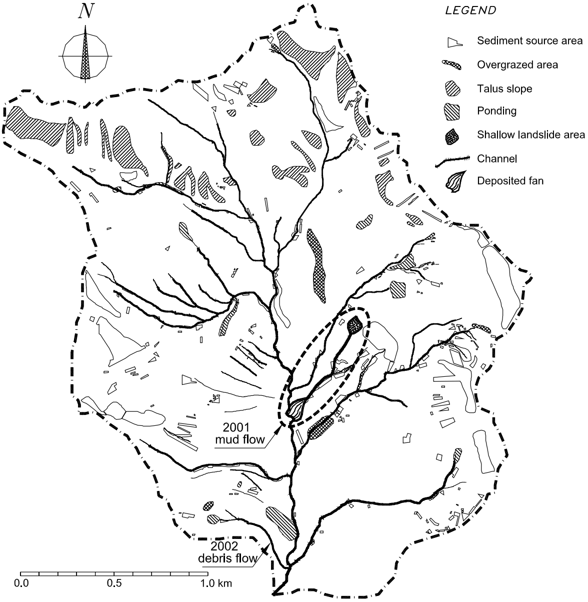

Fig. 1: Map of the Rio Cordon basin showing sediment source areas

The climatic conditions are typical of Alpine environments. Precipitation occurs mainly as snowfall from November to April. Runoff is usually dominated by snowmelt in May and June but summer and early autumn floods represent an important contribution to the flow regime. Usually late autumn, winter and early spring lack noticeable runoff.

Facilities for monitoring water discharge, suspended sediment and bedload transport at the Rio Cordon experimental station have been detailed described in previous papers (Fattorelli *et al*., 1988; D'Agostino & Lenzi, 1996; Lenzi *et al*., 1999, 2000). Measurements are taken by

separating coarse bedload minimum size (20 mm diameter) from water and fine sediment. 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. The volume of coarse bedload is measured at close time intervals less than 10 min by 24 ultrasonic sensors fitted on a fixed frame over the storage area (Lenzi *et al*., 1999). Suspended sediment is measured by two turbidimeters: a Partech SDM-10 light absorption instrument installed in the outlet channel working since the early years of station operation, and a light-scatter turbidimeter (type Hach SS6), installed in 1994 in the inlet flume. Flow samples are gathered automatically using a Sigma pumping sampler installed at a fixed position in the inlet channel.
Previous studies in the Rio Cordon have focused on bedload data (D'Agostino *et al.*, 1994; Rickenmann *et al*., 1998; Asti, 1999; D'Agostino & Lenzi, 1999; Lenzi *et al*., 1999), morphological structure and sedimentology of the stream bed (Lenzi *et al*., 1997; Lenzi, 2001), analysis of sediment sources (Dalla Fontana & Marchi, 1994, 1998, 2003) and particle transport distances (Lenzi & D'Agostino, 1998; Lenzi, in press). Finally, suspended sediment concentrations and yields from single flood events have also been analyzed (Asti, 1999; Lenzi & Marchi, 2000; Lenzi, 2000; Lenzi *et al.*, in press).

Sediments in the Rio Cordon basin are supplied from a number of distinctive source areas (Fig. 1) which have been mapped and monitored since 1987 by field surveys of their main features (i.e. area, elevation, slope and vegetation cover). For each area, sketches, photographs and sediment samples were taken (Billi *et al*., 1998). Their particle-size distribution showed that the material of active sediment sources is widely variable from silt to gravel. Active sediment sources are mainly bare slopes, overgrazed areas, shallow landslides, eroded stream banks and minor debris flow channels. Sediment sources cover an area of 0.262 km^2, i.e. 5.2% of total basin area. In the Rio Cordon basin the rocky slopes commonly do not directly supply sediment to the stream channel. At most sites, sediment eroded from rock cliffs is temporarily stored as scree deposits on talus slopes. The map of sediment source areas was digitalized and the data processed by a Geographic Information System in order to investigate their distribution with respect to the channel network (Dalla Fontana & Marchi, 1994, 1998). About 50% of the total sediment sources area is located upstream of a median, low gradient belt where conditions favourable to deposit prevail. For this reason, the basin headwaters, regardless of the local intensity of the erosion processes, provide a minor contribution to the sediment yield (Dalla Fontana & Marchi, 2003).

RECORDED FLOOD EVENTS AND SEDIMENT AVAILABILITY

From 1987 to 2002 – 17 years – twenty floods characterized by coarse bedload transport (grain size greater than 20 mm) have been recorded at the measuring station. Hydrological and sediment load data of the flood events are shown in Table 1.

In order to evaluate the occurrence frequency of these events, the return interval of each flood was estimated from values of annual maximum instantaneous water discharge over 17 years. The lognormal distribution was the found to provide the best fit, and its parameters were calculated by using the software STATISTICA 6. Return intervals of bedload volumes were also estimated considering the annual maximum volumes, although bedload data do not actually derive from independent events. Again, the lognormal distribution was the best fitting one (Fig. 2). Returns intervals of peak discharges and bedload volumes are reported for each flood in Table 2.

Almost irrelevant bedload transport was recorded during July 1988, May 1990, May 1994 and June 1997 floods. The events characterized by a peak discharge with a return interval of one to five years and by an hourly bedload rate not exceeding 20 m^3 h^{-1} were defined by Lenzi *et al*. (1999) and by D'Agostino & Lenzi (1999) as "ordinary".

By contrast, the 14 September 1994 flood can be considered "exceptional" since it presented an average hourly bedload rate of 225 m^3 s^{-1} with a peak water discharge of 10.4 m^3 s^{-1} . This flood features a very short duration and very high, infrequent flow rate (R.I. = 60 yr), with a total bedload volume (900 m^3) which is huge but not that extraordinary (R.I. = 29 yr).

The October 1987 event presents the second largest peak flow (Q_p = 5.2 m^3 s^{-1}; R.I. = 5.3 yr), 8 hours of bedload transport duration but only an "ordinary" bedload volume yield (54.8 m^3, R.I. = 2.9 yr). Before September 1994, another important flood occurred in July 1989 (Q_p = 4.4 m^3 s^{-1}; R.I. = 3.6 yr) and given its long duration (27 hours) delivered a massive bedload yield (85 m^3, R.I. = 3.8 yr).

Tab. 1: Main hydrological and hydraulic features of the major recorded floods: Q_p, peak discharge; R_e, effective runoff (water runoff volume above the threshold discharge for bedload in the flood hydrograph); BL, coarse bedload volume (volume of the deposit including voids); SSL, suspended sediment load volume; T_{BL}, duration of coarse bedload transport; BL_R, mean bedload rate; SSC_{max}, maximum suspended sediment concentration; Q_{cr1}, critical discharge for bedload entrainment; Q_{cr2}, end of bedload transport critical discharge

	Q_p (m^3s^{-1})	R_e (10^3m^3)	BL (m^3)	SSL (m^3)	T_{BL} (hours)	BL_R m^3 h^{-1}	S.S.C.$_{max}$ (g l^{-1})	Q_{cr1} (m^3s^{-1})	Q_{cr2} (m^3s^{-1})
11/10/1987	5.2	79.9	54.8	49.7	8.0	6.9	-	1.80	3.80
15/07/1988	2.4	-	1.0	-	-	-	-	-	-
03/07/1989	4.4	103.4	85.0	84.5	27.0	3.1	-	2.20	2.70
22/05/1990	0.9	-	1.0	-	-	-	-	-	-
17/06/1991	4.0	57.9	39.0	25.7	20.0	2.0	3.74	2,00	2.40
05/10/1992	2.9	21.5	9.3	1.8	10.0	0.9	1.20	1.90	2.10
02/10/1993	4.3	30.7	13.7	15.5	6.0	2.3	1.65	2.30	3.70
18/05/1994	1.8	5.4	1.0	1.0	12.0	0.1		1.60	1.61
14/09/1994	10.4	26.6	900.0	918.9	4.0	225.0	57.89	1.80	3.30
13/08/1995	2.7	1.8	6.2	37.1	1.0	6.2	6.56	1.80	2.00
16/10/1996	3.0	22.0	57.0	111.1	15.0	3.8	15.45	1.80	2.00
27/06/1997	1.5	-	1.0	-	-	-	-	-	-
07/10/1998	4.7	91.8	300.0	148.5	17.0	17.6	4.94	1.98	2.50
20/09/1999	3.7	10.4	19.2	19.2	6.4	3.0	-	1.68	1.98
12/10/2000	3.3	110.6	55.6	53.6	35.0	1.6	2.13	1.23	1.56
11/05/2001	1.5	8.5	80.0	384.0	13.0	6.2	13.83	1.14	1.33
20/07/2001	2.0	15.0	20.9	45.2	4.7	4.5	8.24	1.59	1.64
04/05/2002	2.3	29.4	27.4	46.4	20.0	1.4	9.90	1.51	1.55
16/11/2002	2.3	18.9	10.1	20.5	14.5	0.7	9.29	1.55	1.57
27/11/2002	2.8	70.3	69.1	141.0	30.0	2.3	9.91	1.55	1.82

Eleven events were monitored after the large event of September 1994. One of them (June 1997) caused very little bedload transport (1 m^3) because of its small peak flow and short duration. The October 1998 event (Q_p = 4.7 m^3 s^{-1}, R.I. = 4.3 yr) is similar in magnitude to the October 1993 flood, but had a longer duration. Its bedload volume (300 m^3; R.I. = 10 yr) is about one order of magnitude greater than that transported during the October 1993, and is the second largest volume recorded. The "mild" event (Q_p = 3 m^3 s^{-1}; R.I. = 1.8 yr) of October 1996 nonetheless features a considerable bedload volume of 57 m^3 (R.I. = 3 yr).

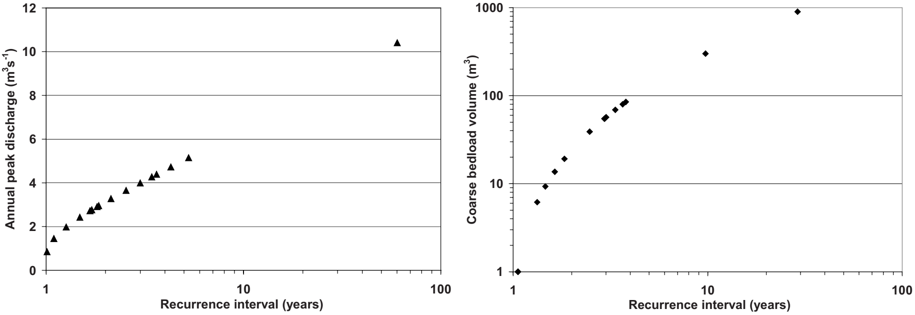

Fig. 2: Magnitude-frequency relationship for annual maximum peak discharge and annual maximum coarse bedload volume using the lognormal distribution

Tab. 2: Return intervals of the recorded floods: Q_p, peak discharge; $R.I._{Qp}$, peak discharge return interval; BL, coarse bedload volume; ; $R.I._{Qp}$, coarse bedload volume return interval.

	Q_p (m^3s^{-1})	R.I. $_{Qp}$ (yr)	BL (m^3)	$R.I._{BL}$ (yr)
11/10/1987	5.2	5.3	54.8	2.9
15/07/1988	2.4	1.5	1.0	1.1
03/07/1989	4.4	3.6	85.0	3.8
22/05/1990	0.9	1.0	1.0	1.1
17/06/1991	4.0	3.0	39.0	2.5
05/10/1992	2.9	1.8	9.3	1.5
02/10/1993	4.3	3.4	13.7	1.6
18/05/1994	1.8	1.2	1.0	1.0
14/09/1994	10.4	60.0	900.0	29.0
13/08/1995	2.7	1.7	6.2	1.3
16/10/1996	3.0	1.8	57.0	3.0
27/06/1997	1.5	1.1	1.0	1.1
07/10/1998	4.7	4.3	300.0	9.7
20/09/1999	3.7	2.5	19.2	1.8
12/10/2000	3.3	2.1	55.6	3.0
11/05/2001	1.5	1.1	80.0	3.7
20/07/2001	2.0	1.3	20.9	1.9
04/05/2002	2.3	1.4	27.4	2.1
16/11/2002	2.3	1.4	10.1	1.5
27/11/2002	2.8	1.7	69.1	3.4

Other important floods with large bedload yields occurred in October 2000 and May 2001. The former had a long duration (35 hr), relatively high peak discharge ($Q_p = 3.3$ m^3 s^{-1}; R.I. = 2.1 yr) and a bedload accumulation of 56 m^3 (R.I. = 3 yr); the latter features only 1.5 m^3 s^{-1} of peak discharge (R.T. = 1.1 yr) but 80 m^3 of bedload (R. I. = 3.7 yr). In 2002, three relatively small floods (R.I. < 1.7 yr) occurred: on May 4th , and on 16th and 27th November. The last one, characterized by a 30 hours duration and a peak discharge $Q_p = 2.8$ m^3 s^{-1} (R.I. = 1.7 yr), transported 69 m^3 of coarse bedload (R. I. = 3.4 yr).

In Fig. 3 a graphical comparison between return intervals for water discharge and bedload volumes of all the flood events is shown. Most of post-1994 points fall above the equality line, whereas most pre-1994 data plot below. Indeed, September 1994 appears to represent a sort of threshold for bed load transport in the Rio Cordon basin. In fact such an low frequency event (R.I. = 60 yr), the largest recorded during the study period, altered the stream geometry (Lenzi, 2001) and the sediment-supply characteristics of the basin.

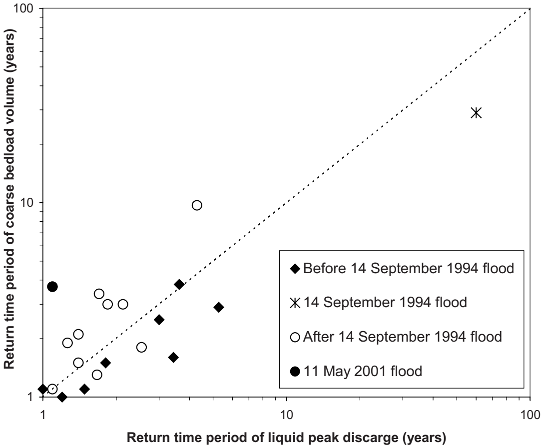

Fig. 3: Return time period of liquid peak discharge versus return time period of coarse bedload volumes of the Rio Cordon registred floods

After the 14 September 1994 flood event, a survey of sediment sources areas was performed in order to identify reactivated and newly-formed sediment sources. Slope instability phenomena were rather limited and consisted mainly of small debris flows and shallow landslides in grass-covered colluvium. From a field survey immediately after the event, the main streambed appeared to have represented the principal sediment source, but minor bank erosion and several bank failures were observed along the main stream and some tributaries. The area of reactivated sediment sources (77.8 m^2) exceeded that of the new ones (10.1 m^2). New and reactivated sediment sources on the stream network or connected to the channels were affected by the largest sediment delivery. However, the occurrence of non-active sediment sources on channels suggest that the stability of at least some stream reaches was not affected by the September 1994 flood.

An important new sediment source formed on 11 May 2001 – simultaneously with a flood event in the main channel – during an intense snowmelt event without rainfall following a very snowy winter. Soil saturation mobilized a shallow landslide covering an area of 1905 m^2

which then turned into a mud flow moving along a small tributary (Fig. 1). A debris fan whose volume was assessed to be 4176 m^3 formed at the confluence with the Rio Cordon (Fig. 4), thus feeding the main channel with medium and fine sediment.

TEMPORAL TRENDS IN THE BEDLOAD TRANSPORT

The main hydrological and sedimentological data of floods recorded in the Rio Cordon from 1987 and 2002 are shown chronologically in Figure 5, where limited and unlimited sediments supply periods are highlighted, separated by the September 1994 event. During this extreme event, the channel bed was the main source of sediment for bedload transport (Lenzi *et al.*, 2000; Lenzi, 2000) mostly because such a very high discharge was able to destroy the streambed armour layer formed over the years. Also, during the September 1994 flood many old sediment sources were reactivated and new ones were created, and this effect is clearly seen after 1994. Fine and medium size sediments eroded from the hillslopes 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; in fact – as discussed above – these events had higher sediment loads than pre-1994 floods with similar water discharges.

Fig. 4: Front view of the May 2001mud flow fan delimitated by the Rio Cordon main channel

Analogously, quasi-unlimited sediment supply conditions occurred in the Rio Cordon as a consequence of the 2001 mud flow. Beside the May 2001 event's relatively very high bedload transport, this availability of sediments from the newly-formed fan likely allowed the small July 2001 flood to mobilize 21 m^3 of bedload material. The three floods in 2002 show high sediment loads too, and this may be partly an inheritance of the May 2001 mud flow, even though a small debris flow that occurred close to the measuring station in concomitance with the November 2002 event might have contributed considerably to this flood's high bedload transport.

However, an analysis based on water peak discharge is not accurate enough when flood duration is highly variable, and a more integrated hydrological parameter is needed. The concept of effective runoff proposed by Rickenmann (1994, 1997) appears promising for Rio Cordon's bedload data. Effective runoff was determined for each flood as the hydrograph volume exceeding the detected threshold discharges (Q_{cr1-2}) from the beginning to the end of the bedload transport (Billi *et al*., 1998). Taking the effective runoff (R_e) and the volume of the coarse bedload (BL) for the pre-September 1994 events, a simple linear relation can be established:

$$BL = 0.7 * 10^{-3} R_e \tag{1}$$

where BL and R_e are expressed in m^3 ($R^2 = 0.93$). Considering instead all the floods, an extremely wider scatter result from the correlation, thus suggesting that some non-hydrological controls have altered the bedload response of the basin/channel.

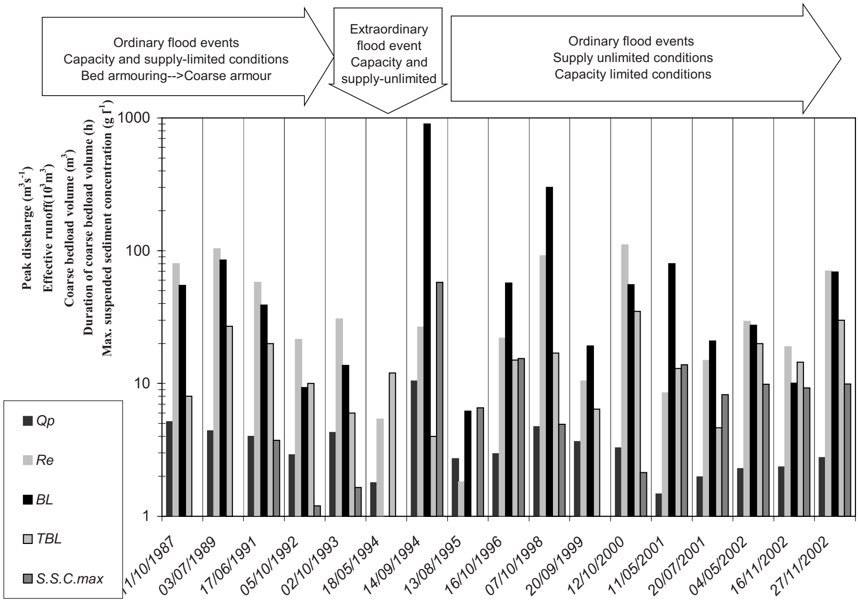

Fig. 5: Main hydrological and sedimentological data of floods recorded in the Rio Cordon: *Qp,* peak water discharge; *Re,* effective runoff,; *BL,* coarse bedload volume; *TBL,* bedload transport duration; *SSC max,* maximum suspended sediment concentration.

This become evident plotting in a semi-logarithmic graph the ratio BL/R_e (with R_e expressed as 10^3 m^3) for each flood (Fig. 6).

The BL/R_e ratio exhibits two decreasing trends over the 1986-1993 and 1995-2002 periods, and its value for the September 1994 flood is more than one order of magnitude larger than in the other floods, except for the May 2001 event. Before 1994, the ratio was always below 1, whereas afterward it was mostly above 1, as a response to such a destabilizing event. The decreasing trends can be ascribed to the "cleaning up" of sediment from the streambed and other active sources by "ordinary" events. However, the trend line shown for the post-1994 events might be not entirely significant, because of the sediment supplying effect of the May 2001 event which may have "raised" the ratios thereafter, but the scarcity of points prevents any definitive assertion.

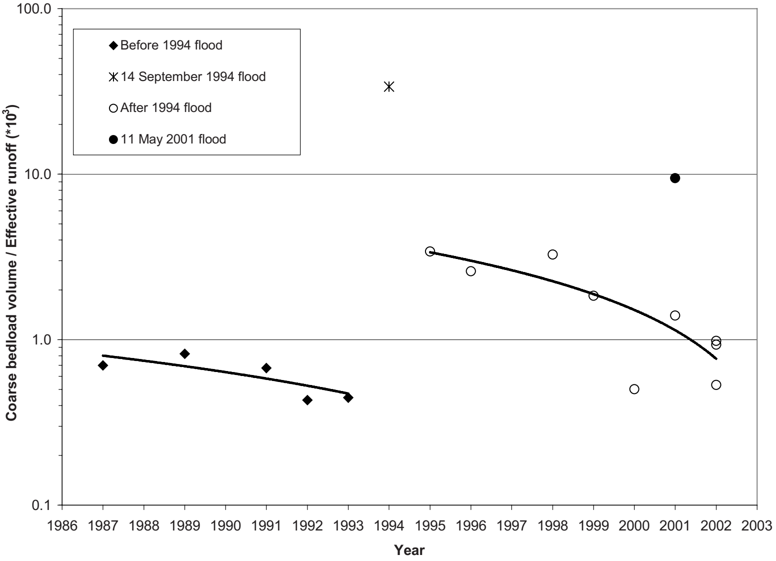

Fig. 6: The ratio coarse bedload volume / effective runoff (*10^3) over 17 years of recording.

Therefore, the analysis of bedload production through the effective runoff confirms in a dimensionless manner what already envisaged in the previous section about the role of sediment supply derived from the September 1994 extreme event and from the May 2001 mud flow, providing also sounder quantitative insights about dynamics and temporal evolution of the stream-hillslopes coupling processes.

CONCLUSIONS

Hillslope and tributary processes as landslides and debris flows may donate characteristics of unlimited or quasi-unlimited conditions to medium intensity, more frequent flood events which otherwise would transport only small amounts of sediment. This has been confirmed and given a statistical evaluation by analyzing twenty flood events with bedload transport in the Rio Cordon experimental basin. Limited and unlimited sediments supply periods have been highlighted, separated by the September 1994 extreme event. The analysis demonstrates both the control exerted by sediment availability on bed load volumes and the persisting long-term impact of major floods on mountain streams.

ACKNOWLEDGEMENTS

The ARPAV Center of Belluno and the Avalanche Center of Arabba (Veneto Region, Italy), and particularly Dr. A. Lucchetta, and Dr. F. Sommavilla are kindly acknowledged for providing the Rio Cordon data. We are grateful to Dr.ssa T. Corso and Dr. W. Testor for their assistance and field work.

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