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ANALYSIS OF SEDIMENT TRANSPORT IN EXPERIMENTAL ALPINE AND ANDEAN CATCHMENTS

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ABSTRACT

Sediment transport occurring in small, high-gradient streams is one of the most important aspects to be evaluated for land use planning in mountain areas. The research was conducted in two experimental catchments, comparable for dimensions. The Rio Cordon is a small basin in the Dolomites (Italian Alps). Since 1986 an instrumented site has been operating to measure flow discharge, bedload and suspended sediment transport. In September 1994, an extraordinary (T_R>50 years) flood produced 900 m^3 of coarse sediment and clearly affected the successive sediment transport: 1996, 1998 and 2000 ordinary floods showed higher sediment loads compared to similar pre-1994 floods. The Tres Arroyos is a 5.93 km^2 Andean catchment (Chile). Water discharge, suspended and coarse sediment load have been monitored since 1997. The paper presents a comparison between the two basins of data regarding suspended sediment and bedload related to flood characteristics and sediment sources. Sediment transport characteristics, relationship between total load, bedload and suspended sediment load in the two catchments, reflect the differences in precipitation patterns, flow regimes and vegetation cover.

Key words: Sediment transport; Suspended sediment load; Bedload; Floods; Instrumented basin; Alpine and Andean catchments

INTRODUCTION

Small, steep headwater basins are of relevant importance in the context of mountain watershed management, as most sediment transfer from slopes to the stream network takes place here. Nevertheless, a lack of experimental data still exists on hydrological and sediment transport processes in small mountain streams. This is due to the problems associated to field investigations to be carried out in hostile physiographic conditions and, in particular, to the difficulty of devising proper techniques for measuring bedload in such steep, coarse-grained streams. However, in recent years new or improved approaches to bedload measurement have been developed in some small instrumented watershed of the Alps and also of the Andes. New techniques used include the indirect measurement of bedload rate by means of acoustic or seismic sensors (Bänziger and Burch, 1990; Govi *et al.*, 1993), the monitoring of the distances travelled by magnetic and radio tracers (Schmidt and Ergenzinger, 1992) and the

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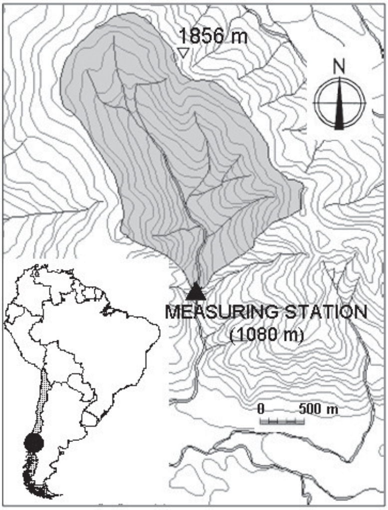
complete measurement of bedload and suspended transport in especially designed gauging stations (Fattorelli *et al*., 1988).
The aim of this paper is to analyse results from suspended and bed load measurements in two mountain basins of comparable area equipped with different facilities for sediment transport measurement, one lying in South of Chile, the second in the Dolomites (Italy, Eastern Italian Alps).

MATERIAL AND METHODS

Study basins

The research was conducted in the Rio Cordon catchment (Fig. 1b), a small water course (5 km^2) of the Dolomites (Northeastern Italian Alps) and in the Rio Tres Arroyos catchment (5.93 km^2) located in the Andes of South of Chile (Fig. 1a). The main physiographic characteristics of the two instrumented watersheds are reported in Table 1.



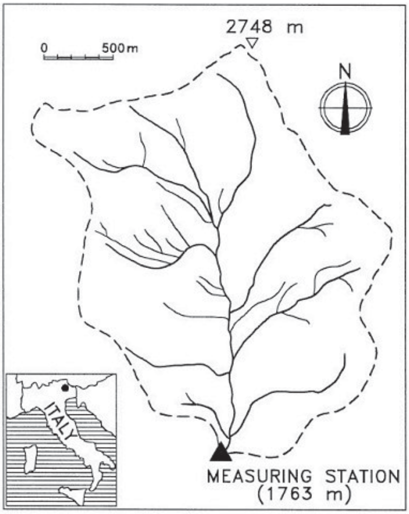


Fig. 1: 1a) Rio Tres Arroyos location and basin map; 1b) Rio Cordon location and basin map

Tab. 1: Main characteristics of the Rio Cordon and Rio Tres Arroyos basins

		Rio Cordon	**Rio Tres Arroyos**
Catchment area	(km^2)	5.00	5.93
Minimum elevation	(m.a.s.l.)	1763	1080
Maximum elevation	(m.a.s.l.)	2748	1856
Length of the main stream	(km)	2.84	3.5
Mean gradient of the main stream	(%)	17	22
Annual precipitation	(mm)	1100	2203
Maximum water discharge measured	(m^{3}s^{-1})	10.4	14.0
Mean annual temperature	(° C)	2.0	8.5

The solid geology of the Rio Cordon 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.
Herbaceous associations cover 61% of the watershed surface, while shrubs are relatively widespread (18%). Forest stands are found only in the lower part of the watershed occupying 7% of its area; 14% of the catchment consists of bare land.
The climatic conditions are typical of an Alpine environment. 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 events (Lenzi *et al.*, 1990; Dalla Fontana, 1992).
The different layers of volcanic rocks that characterize the geology of the Rio Tres Arroyos are strongly associated to the volcanic activity of the area. The more superficial rock formations originated during the Pleistocene y Holocene, and are associated to the nearby Lonquimay volcano (Iroumé, 1997; 2003).
Soils in the basin originated from volcanism and have high sand content (68% in average) and high infiltration capacity, while loam and clay contents are 30 and 2% respectively. Near the 79% of the area is covered with *Nothofagus spp.* broadleaved native forests. Above the tree line vegetation disappears, and the highest altitudes correspond to bare lands (21% of the area) covered with sandy volcanic ashes.
Precipitation occurs all year round, although the period April-September concentrates more than the 72% of the annual total. Part of the annual precipitation falls as snow but runoff is dominated by rainfall with very little snowmelt participation.

The Rio Cordon and the Rio Tres Arroyos measuring stations

The Rio Cordon facility for measuring sediment transport operates by separating coarse bedload transport from fine sediment and water (Fattorelli *et al.*, 1988; D'Agostino and Lenzi, 1996; Lenzi *et al.*, 1999, 2000). The separation is obtained by means of an inclined grid where coarse material (exceeding 20 mm) slides over the grid and accumulates in a storage area where its volume is measured by 24 ultrasonic sensors placed on a fixed frame (Lenzi *et al.*, 1999). Further details about the facility can be found in the papers quoted above. Single-flood suspended and bedload data have already been analyzed (Lenzi *et al.*, 1999; D'Agostino and Lenzi, 1999; Asti, 1999; Lenzi *et al.*, 2000; Lenzi and Marchi, 2000; Lenzi, 2000, 2001).
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. The sampler is set to pick up flow samples automatically at fixed time intervals when a discharge threshold is exceeded. In addition, samples are manually collected during floods at selected verticals using a USDH 48 bottle sampler (Lenzi and Marchi, 2000; Lenzi, 2001).
The water level gauging station at the Rio Tres Arroyos corresponds to a natural section located at 1080 m.a.s.l., which controls a 5.93 km² catchment area (Iroumé, 1997). The gauging station consists in a pressure sensor connected to a continuous data logger.

Relationships between suspended sediment concentration and discharge and bed load and discharge have being developed to calculate suspended and bed load transport (Iroumé, 2003). The suspended sediment concentration is obtained from 0.33 litre water samples manually collected in the location of the Rio Tres Arroyos gauging station. In each occasion the sample is completed from three sub-samples obtained from different profiles within the mainstream. These profiles coincide with the position where the current meter and the bed load sampler are located in each campaign. A Global Water WQ700 turbidimeter is also installed at the gauging station although this data has not been used because of a lack of consistent relationships between suspended sediment concentrations and turbidity. The bed load has systematically been measured at the location of the gauging station using a Helley-Smith sampler.

RESULTS

Floods, sediment transport and annual sediment budget in the Rio Cordon

Hydrological and sediment load data of the flood events recorded at the measuring station are shown in Lenzi *et al*., (Tab. 2, this volume); the September 1994 flood represents the most severe flood recorded since the station was installed in the Rio Cordon. The event was caused by high intensity rainfall with an estimated recurrence interval of 60 years.

Besides rainfall-caused flows, snowmelt runoff may be a source of conspicuous contribution to the annual suspended sediment yield. Abundant suspended sediment transport was recorded during rapid snowmelt phases caused by high temperature and rainfall. In contrast, the combination of early snowfalls, permanent snow cover through the winter and slow snowmelt with no rain would lead to scant suspended sediment load. The two turbidimeters collect measurements every 5 minutes during flood times; in order to derive the daily values of suspended solid load needed for working out annual budgets, an empirical correlation between water discharge and S.S.C. was used to cover periods characterised by flows lower than a certain discharge threshold (i.e. 0.8 m^3s^{-1}) and not included on Table 2 (Lenzi *et al*., this volume). Different relationships were obtained for summer-autumn floods and for spring snowmelt runoff; they both show quite a noticeable scatter, but with less dispersion for the snowmelt data. The S.S.C. - water discharge correlation for snowmelt flows is reported on equation 1:

$$S.S.C. = 2.198 \ln Q + 4.004 \tag{1}$$

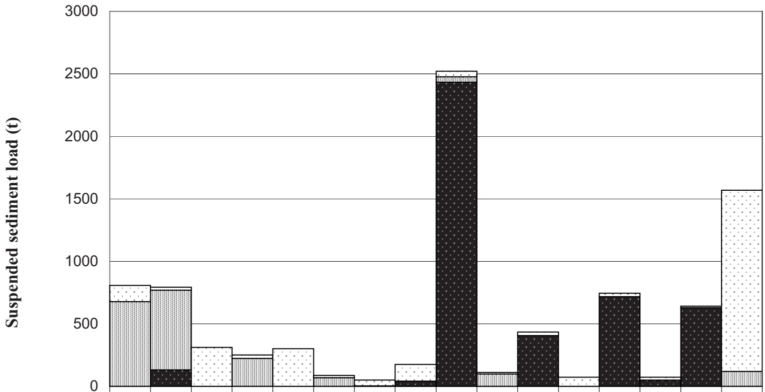
where S.S.C. is the suspended sediment concentration expressed in mg l^{-1} and Q is the water discharge in m^3 s^{-1}. Equations (2) and (3) were obtained from summer and autumn data respectively:

$$S.S.C. = 6.719 \ln Q + 0.683 \tag{2}$$

$$S.S.C. = 2.758 \ln Q - 3.967 \tag{3}$$

Considering the Rio Cordon hydrological regime, i.e. a typical small Alpine catchment dominated by snowmelt runoff and by summer and early autumn floods, 31 August and 30 November have been assumed as the dates for the end of summer and autumn respectively. Since winter is characterised by very low flows, the period December to March has not been taken into consideration for the sediment contribution. The reactivation of solid transport after winter coincides with the onset of snowmelt and begins in April, although its effects are most evident in May. Snowmelt generally lasts for 10-15 days.

Annual budgets of the suspended solid transport for the period 1986-2001 – divided in snowmelt, summer and autumn seasons – are reported in Figure 2. Comparing the 16 years, high suspended solid transport occurred in 1994, 2001, 1986, 1987 and 1998 during which the suspended load was respectively equal to 2521.5, 1568.5, 806.9, 792.1 and 744.7 t year^{-1}.
Summer and autumn contributions were substantial in 1986, 1987, 1994 and 1998; in contrast, 2001 featured a snowmelt flood accounting for all the suspended load measured that year. A marked variability can be observed of the suspended solid transport associated with snowmelt floods: years 1988, 1990 and 2001 were characterised by a very important role for this kind of runoff, especially if compared with 1995 and 2000 (Fig. 2).



	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Snowmelt	128.5	21.7	312.7	27.8	302.1	18.8	45.8	134.4	43.7	12.7	30.7	73.9	26.5	23.1	12.2	1449.
Summer season	678.4	638.7	0.0	223.9	0.0	68.1	0.0	0.0	45.1	98.1	0.0	0.0	0.0	0.0	0.0	119.3
Autumn season	0.0	131.7	0.0	0.0	0.0	0.0	4.8	41.1	2432.	0.0	405.5	0.0	718.2	50.4	629.4	0.0

Fig. 2: Seasonal suspended sediment yield (t) registered at the Rio Cordon station

From Table 2 it is apparent that 76% of the total sediment load which occurred over 16 years (11744.2 t) was in form of suspended transport; this rate decreases to 64% if calculated considering only the flood events. However, most of this volume was supplied during only two single floods – September 1994 and May 2001 – respectively with 27 and 11%. The sediment relative density used for converting bedload data – that are volumetric at the recording station– into weight values is 2.65 t m^{-3}, and the porosity of the bedload heap adopted to obtain void-less volumes is 65%.

Tab. 2: Annual characteristics of sediment production in the Rio Cordon

Year	Suspended sediment load (t)	Bedload (t)	Total sediment load (t)
1986	806.9	0.0	806.9
1987	792.1	85.6	877.7
1988	312.7	0.0	312.7
1989	251.8	145.6	397.3
1990	302.1	0.0	302.1
1991	86.9	67.2	154.1
1992	50.6	15.5	66.1
1993	175.4	17.2	192.7

1994	2521.5	1543.4	4064.8
1995	110.8	10.3	121.1
1996	436.2	94.7	530.9
1997	73.9	0.0	73.9
1998	744.7	516.8	1261.4
1999	73.4	32.7	106.1
2000	641.6	92.2	733.7
2001	1568.5	174.0	1742.5
Total	8949.1	2795.1	11744.2

Such a result confirms the strong link between suspended load and the availability of sediment sources. During the first peak of the 14 September 1994 event, suspended transport was the dominant process. During the second – and much higher – peak of the same flood suspended sediment was still important but the massive water discharge led to very large bedload rates. If the two phases of the flood are considered together, suspended load accounts for about 61% by weight of the total sediment yield. This extreme event destroyed the streambed armouring and caused channel morphology changes (Lenzi, 2001). 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 hillslopes were stored in the stream network as the flood ceased and were subsequently removed and transported downstream by ordinary floods in 1996, 1998 and 2000; in fact these events had higher sediment loads than pre-1994 floods with similar water discharges. Therefore post-1994 average annual suspended load is higher than for the preceding events (Tab. 3 and Fig. 3).

Tab. 3: Mean annual values of suspended load, bedload and total sediment load calculated for different periods

	Suspended load (t)	**Bedload (t)**	**Total sediment load (t)**
Annual average 1986 -1993	347.3	41.4	388.7
Year 1994	2521.5	1543.4	4064.8
Annual average 1995 - 2000	346.8	124.5	471.2
Year 2001	1568.5	174.0	1742.5

Analogously, quasi-unlimited sediment supply conditions in the Rio Cordon as a consequence of the mud flow which occurred in May 2001 allowed the July 2001 flood to mobilize 77.7 t of sediment in water suspension. Before 2001, a snowmelt flood was never able to generate bedload transport in the Rio Cordon. Snowmelt flows usually range between 0.6 and 1.0 m^3s^{-1}. In the May 2001 event, water discharge exceeded 1.0 m^3s^{-1} for more than 24 hours, peaking at 1.47 $m^3\ s^{-1}$. Both suspended load (1016.2 t) and bedload (137.8 t) were exceptionally large for such a small flood.

Averaging 16 years of data, the mean annual specific sediment yield turns out to be 146.8 t km^{-2} $year^{-1}$. However, it must be pointed out that this value includes the 1986-1993 period characterized by ordinary floods during which the mean sediment production was 77.7 t km^{-2} $year^{-1}$, the massive sediment yield in 1994 (813.0 t km^{-2} $year^{-1}$) and finally the 1995-2001 period featuring high annual loads (130.6 t km^{-2} $year^{-1}$). The highest annual values correspond to 1994 (813.0 t km^{-2} $year^{-1}$), 2001 (348.5 t km^{-2} $year^{-1}$) and 1998 (252.3 t km^{-2} $year^{-1}$). The proposed interpretation is that high-magnitude, low-frequency flows reactivating or creating new sediment sources have a direct effect on sediment supply conditions and then can substantially increase the amount of sediment transported by subsequent floods. Once streambed equilibrium gets dramatically altered, many years may be needed before a new bed stability is achieved.

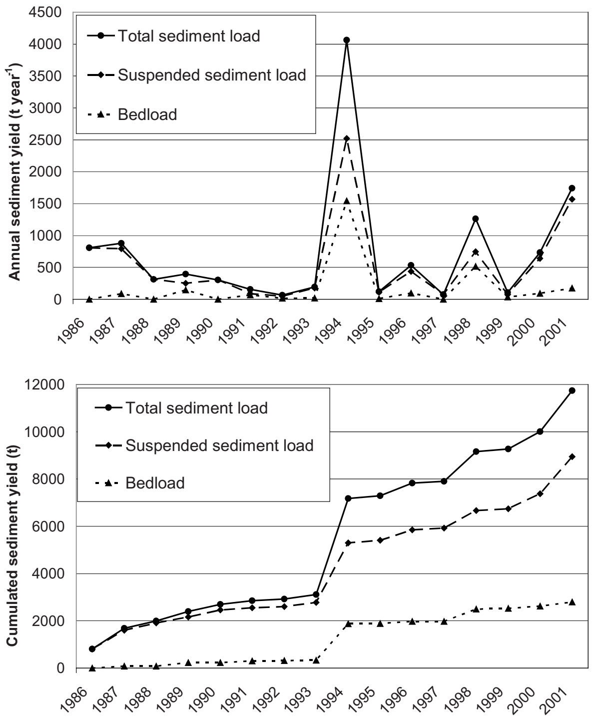


Fig. 3: Annual (above) and cumulated (below) sediment yield measured in the Rio Cordon over 16 years

Floods, sediment transport and annual sediment budget in the Rio Tres Arroyos

The S.S.C. - water discharge correlation at the Rio Tres Arroyos gauging station (Iroumé, 2003) is reported on equation 4:

$$S.S.C. = 27.36\, Q^{1.899} \tag{4}$$

where S.S.C. is the suspended sediment concentration expressed in mg l^{-1} and Q is the water discharge in $m^3\ s^{-1}$.
The bedload – water discharge relationship is presented in equation 5:

$$Q_B = 138.18\, (Q - Q_{crit})^{1.93} \tag{5}$$

where Q_B is the instantaneous bedload rate expressed in g s^{-1}, Q the water discharge in $m^3\ s^{-1}$ and Q_{crit} the critical water discharge for initiation of bed material movement in $m^3\ s^{-1}$. Using bedload sampling data and the relationship proposed by Bathurst (1987), the critical water discharge for initiation of bed material movement was estimated in 0.0875 $m^3\ s^{-1}$ (Iroumè, 2003).
From Table 4 it can be noticed that 29.6% of the total sediment load which occurred over 5 years (10691.9 t) was in form of suspended transport.

Tab. 4: Annual characteristics of sediment production in the Rio Tres Arroyos

Year	Suspended sediment load (t)	Bedload (t)	Total sediment load (t)
1998	29.5	254.1	283.6
1999	282.5	1350.8	1633.3
2000	1308.3	2843.5	4151.8
2001	1181.1	2005.7	3186.8
2002	363.2	1073.2	1436.4
Total	3164.6	7527.3	10691.9

The participation of suspended sediment load in total sediment load varied between 10.4% in 1998 to 37.1% in 2001. Such results confirm the link between suspended load and the availability of sediment sources. The high vegetation cover (79% of the catchment area under broadleaved native forests) and high infiltration capacity of the sandy soils favor subsuperficial flow and reduce erosion so reducing suspended sediment delivery to the streams. Bedload transport originated mainly from erosional processes within the drainage network accounts in average for almost 2/3 of the total sediment load. Only in exceptional high rainfall periods suspended sediment load tend to equal bedload transport. This is the case of an exceptional event registered in July 2001 with an instantaneous peakflow of 14 $m^3 s^{-1}$, which generated 966 and 906 t of suspended and bed load, respectively.

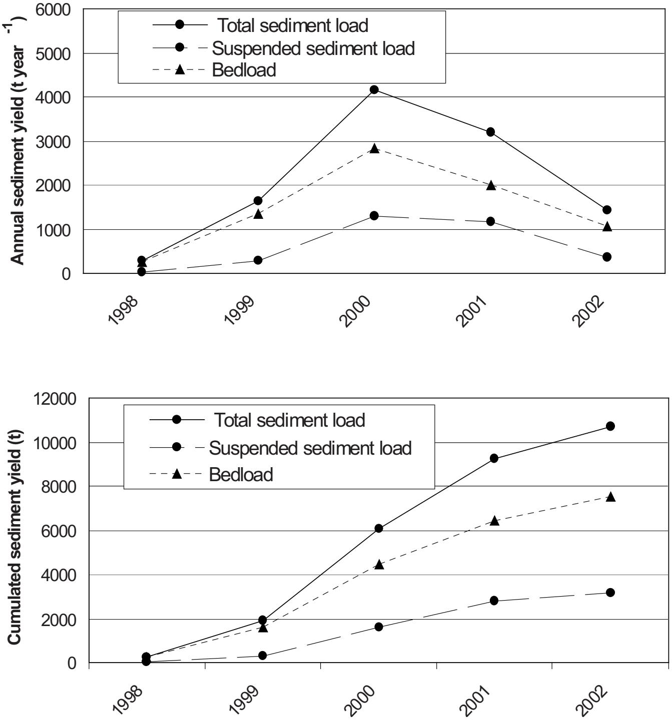


Fig. 4: Annual (above) and cumulated (below) sediment yield measured in the Rio Tres Arroyos over 5 years

Averaging 5 years of data, the mean annual specific sediment yield is 396 t km^{-2} $year^{-1}$, varying from 47.8 t km^{-2} $year^{-1}$ in 1998 to 700 t km^{-2} $year^{-1}$ in year 2000 (Fig. 4). The differences are associated to mean annual discharge and inter-annual discharge variability. In 1998, mean annual discharge was 0.21 m^3 s^{-1} and monthly mean discharge ranged from 0.125 m^3 s^{-1} in January (summer) and 0.296 m^3 s^{-1} in October (spring). In this year, sediment transport was evenly distributed and monthly sediment yields were between 7.7 and 60.8 t $month^{-1}$. In year 2000, mean annual discharge reached 0.58 m^3 s^{-1} and monthly mean discharge varied from 0.208 m^3 s^{-1} in January to 1.21 and 1.35 m^3 s^{-1} in June and July (winter). In this particular year, sediment transport during June and July concentrated the 74% of the annual total amount.

DISCUSSION

The differences in rainfall, hydrological regimes and extent of forest cover seem to explain the differences in sediment load between the Rio Cordon and the Rio Tres Arroyos basins. The mean annual specific sediment yield at the Rio Cordon is 146.8 t km^{-2} $year^{-1}$ (average of 16 years of data) and 396 t km^{-2} $year^{-1}$ at the Rio Tres Arroyos (average of 5 years of data). In average, 76.2% of the total sediment load which occurred over 16 years at the Rio Cordon was in form of suspended transport Rio Cordon, while in 5 years of data collection at the Rio Tres Arroyos, suspended load accounted for the 29.6% of the total sediment load.

This research emphasises the connection between alluvial stream channel processes and the sources of the transported sediments. The key issue is the degree to which the hillslopes and stream channels are coupled (Rice, 1994) and, also, the recurrence interval of the event (Church, 1998). In small, high-altitude basins, the channel may remain decoupled from the adjacent slopes for many years, until an extreme event (like the 1994 flood in the Rio Cordon) inputs a large volume of material to the channel. In low-altitude basins located in rainy areas (mean annual rainfall at the Rio Tres Arroyos is 2300 mm $year^{-1}$ as compared with the 1100 mm $year^{-1}$ of precipitation at the Rio Cordon which occur mainly as snowfall), channel and adjacent hillslopes are connected all year round. At the Rio Cordon, after the 2001 mud flow a substantial amount of sediment is delivered directly to the stream channels from the hillslopes, and the channel will either aggrade or remain unaltered depending on the capacity of future floods to pass the sediment downstream. At the Rio Tres Arroyos, the high vegetation cover and the sandy soils reduce suspended sediment delivery to the streams, and bedload transport originated mainly from erosion processes in the drainage network accounts in average for most of the total sediment load. Only in exceptional high rainfall periods suspended sediment load tend to equal bedload transport.

Two much larger catchments located in the Northeaster Italian Alps (Cordevole at Alleghe lake, 242 km^2, and Boite at Vodo di Cadore, 322 km^2) in the same geographic area and belonging to the same macroclimatic region provide an interesting comparison to the Rio Cordon's sediment yield data. The former presents an average (over the period 1895-1984) of 303 t km^{-2} $year^{-1}$, whilst the latter features a mean value of 227 t km^{-2} $year^{-1}$ calculated between 1958 and 1974. The diversity between these large basins and the Rio Cordon is interesting, and at least two reasons might be involved.

First, the hydrological regimes are markedly different, since the Rio Cordon is a high-altitude catchment (mean elevation 2300 ma.s.l.) where snow-related processes (e.g. ground cover, snowmelt runoff) dominate for most of the year, normally from November to May. Further, the response time of such a small basin is quite short, thus making important flood events occurring during short-duration, heavy rainfall. The flood duration is accordingly small, so

that the flow is capable of transporting sediment down the channel only during a limited time (i.e. few hours), considering also the coarseness of the bed material. On the other hand, larger and lower altitude basins like the Cordevole and the Boite are primarily influenced by autumn cyclonic precipitation, which duration leads to longer flood times. Therefore these rivers have a much longer period of time for transporting sediments downstream, i.e. a water discharge above the mobilization threshold lasts much longer than in Rio Cordon-type catchments.
A second argument for the higher sediment production of the Cordevole and Boite basins concerns the flood history of these basins. In 1965 and 1966 they were affected by two extreme events, with estimated return periods around 50-75 and >150-200 years, respectively. Huge amounts of sediment were transported by these rivers (600-900 t km^{-2} $year^{-1}$) on these occasions, and during the subsequent years the sediment yield was considerably higher than before. In the Rio Cordon, so far only one extraordinary (return period 50-60 years) event has been recorded, i.e. the 1994 summer flash-flood, which nevertheless accounts for 27% of the 16 years of monitoring.

CONCLUSIONS

Data collected in the Rio Cordon for 16 years show that 76% of the total sediment load (8949.1 t of 11744.2 t) was due to suspended sediment transport. A large share of the suspended sediment load was supplied during two flood events, September 1994 and May 2001, with 27% and 11% of the total load respectively. Abundant deposition in channel network at the end of September 1994 flood provided most of the sediments to be eroded during subsequent, smaller floods. A similar pattern was observed after the May 2001 snowmelt event, when a mud flow built a new fan just by the Rio Cordon main channel. The fan then acted as a source of fine sediments in the July 2001 flood, leading to a high suspended load.
At the Rio Tres Arroyos basin, data for 5 years indicate that the 29.6% of the total sediment load (3164.6 t of 10691.9 t) was associated to suspended sediment transport. Channel and adjacent hillslopes are connected all year round, but suspended sediment delivery to the streams is reduced because the high vegetation cover and the high infiltration capacity of the sandy soils of the Rio Tres Arroyos basin, and bedload transport accounts in average for almost 2/3 of the total sediment load. Only in exceptional high rainfall periods suspended sediment load tend to equal bedload transport.
The results of this research emphasise the connection between alluvial stream channel processes and the sources of the transported sediments. Also, allows understanding the differences in sediment transport processes between the Rio Cordon (Italian Alps) and the Rio Tres Arroyos (Chilean Andes) basins, associated to different rainfall totals and types, vegetal covers and hydrological regimes.

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