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Experience from Sediment Transport Monitoring and Investigations in the Rio Cordon

M.A. Lenzi

Dept. Land and Agroforest Environments, University of Padova, Italy

(marioaristide.lenzi@unipd.it / Fax: 39-0498272686 / Phone: 39-0498272675)

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 remote locations. Nevertheless, the understanding of the relationships among mountain catchments characteristics, stream morphology and sediment yield is crucial, especially in Alpine regions, where high-altitude territories are being encroached by human activities, posing a strong need to predict and prevent natural disasters. Therefore measuring facilities providing temporal series of sediment load data in such environments are very relevant from a practical perspective as well as for the scientific community. The aim of this paper is to present almost two decades of flow, suspended and bed-load transport rates recorded at the measuring facility in the Rio Cordon basin (Dolomites, Italian Alps), which have provided more than twenty flood events (characterized by coarse bed-load transport) that have been analyzed focusing on magnitude-frequency analysis of bed-load intensity and volumes, temporal trends of sediment transport related to sediment supply conditions, evaluation of the effective discharge and finally long-term sediment yield.

STUDY SITE AND MONITORING FACILITIES

A long-term water and sediment fluxes monitoring activity is being carried out since 1987 in the Rio Cordon, a small catchment (5 km^2) in the Dolomites (Eastern Italian Alps). The solid geology of the basin consists of dolomite, which provides the highest relief in the catchment, volcaniclastic conglomerates and tuff sandstones. Forest stands are found only in the lower part of the watershed, and cover 7% of the basin area.

The Rio Cordon is a steep (13.6% mean gradient), cobble/boulder-bed channel with a prevalent cascade and step-pool morphology draining a small high-altitude catchment (average elevation 2200 m a.s.l.). The main channel average bed surface grain size distribution is characterized by the following percentiles (in mm): D_{16}= 20, D_{50}= 90, D_{84}= 260, D_{90}= 330 (Lenzi *et al*., 1999, 2004). The mean diameter D_m is 130 mm. The channel width at flood flows, in a typical cross-section just upstream of the station, varies from 5 to 6.7 m, depending on the discharge. Although several factor make difficult the field evaluation of bankfull discharge in steep, cobble/boulder-bed streams like the Rio Cordon, the assumed discharge Q_{bf}= 2.3 m^{3}s^{-1} was estimated to have a recurrence interval of 1.6 years by using the lognormal distribution (Lenzi *et al*., 2004).

Snow-related processes dominate from November to May. However, the response time of such a small basin is very short, thus important flood events occur during intense, short-duration rainfall. Flood duration is accordingly brief, so that the flow is capable of transporting sediment down the channel during only a limited time period (i.e. few hours per year), given the coarseness of the stream bed material.

Sediments in the Rio Cordon basin are supplied from a number of distinctive source areas which have been mapped and monitored since 1987 by field surveys, and cover a 5.2% of total basin area. Active sediment sources are mainly bare slopes, overgrazed areas, shallow landslides, eroded stream banks and minor debris flow channels. After an extraordinary flood event (14 September 1994), a field survey identified the main streambed as the principal sediment source, however minor bank erosion and several bank failures were observed along the main stream and some tributaries.

The facility for measuring sediment transport operates by separating coarse bed-load transport from fine sediment and water (Fattorelli *et al*., 1988; D'Agostino & Lenzi, 1996). 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). Bed-load volume accumulation is continuously measured at 5 minutes intervals by the 24 ultrasonic sensors over the storage area. Liquid discharge is also continuously measured at 5 minutes interval by three different flow gages in the measuring station.

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 & Marchi, 2000; Lenzi, 2001).

From 1987 to 2004 twenty-three floods characterized by bed-load transport (grain size greater than 20 mm) have been recorded at the measuring station.

Previous studies in the Rio Cordon have focused on bed-load transport (D'Agostino & Lenzi, 1999), the morphological structure and sedimentology of the stream bed (Lenzi, 2001), analysis of sediment sources (Dalla Fontana & Marchi, 2003) and particle transport distances (Lenzi, 2004). Suspended sediment concentrations and yields associated with single flood events have also been analysed (Lenzi & Marchi, 2000; Lenzi *et al.*, 2003), and, finally, a magnitude-frequency analysis of bed-load transport has recently been presented (Lenzi *et al.*, 2004).

BED-LOAD TRANSPORT

Magnitude-frequency analysis of bed-load intensity and volumes

In order to evaluate their frequency of occurrence, the return interval of each flood peak was estimated from values of annual maximum instantaneous water discharge. Return intervals of bed-load volumes were also estimated considering the annual maximum volumes. Comparing the return intervals for water discharge and bed-load volumes of all the flood events it appears that, for equivalent former, the latter is higher for most of the post-1994 flood. Indeed, 1994 appears to represent a threshold for bed-load transport in the Rio Cordon basin. On September 14, 1994, a flood presenting a peak water discharge of 10.4 m^3 s^{-1} and a hourly-averaged bed-load intensity of 225 m^3 h^{-1}occurred. This event features a very short duration and a very high, infrequent peak flow rate ($R.I.$ = 53 yr), with a total bed-load volume of 900 m^3 ($R.I.$ = 30 yr). This low frequency event, the largest recorded during the study period, also altered the stream geometry (Lenzi, 2001) and the sediment-supply characteristics of the basin as a whole (Lenzi *et al.*, 2004).

Considering the yearly maximum bed-load volumes transported for each duration - values include porosity about of 0.36 - and treating them as independent values (similarly to what commonly done for rainfall data), the relationship between annual maximum bed-load volumes transported during 1, 4, 5, 12 h and their return period was assessed. The power curves of bed-load partial volume – bed-load duration relative to different return periods (2 – 20 years) show that, for frequent bed-load events ($R.I.$ close to 1), the longer the duration, the larger the yield. As the return interval increases, the period in which similar volumes are delivered decreases rapidly. The shortest bed-load periods, from 1 hour to 4 hours, exhibit very wide ranges in bed-load transported volumes, as large as two orders of magnitude (1-360 m^3 for T_{BL} = 1 hr).

This same evidence can be seen for bed-load intensity where, along with the expected general decrease of intensity for longer duration, the width of the variation band increases. There is a narrow range of intensity variation (between 4 and 8 m^3 h^{-1}) for "ordinary" events ($R.I.$ = 2 years) with durations from 1 to 12 hours. By contrast, short-duration (<4 hr), very infrequent events ($R.I.$ = 20 years) have an intensity of almost 100 m^3 h^{-1}, which is twice that recorded for longer (>4 hr) events of similar frequency (Lenzi *et al.*, 2004).

Bed-load rating curves

Bed-load volume accumulation is continuously measured at 5 minutes intervals by 24 ultrasonic sensors over the storage area. Given the pulsating character of bed-load transport and the settling of clasts forming the sediment heap, the hourly increase of bed-load volume was evaluated and was coupled to water discharges averaged over the antecedent 60 minutes throughout each flood event.

The bed-load intensities data are grouped into three categories: September 1994 event, pre-1994 and post-1994 flood events. It is apparent that the former are displaced much higher (up to 25 kg s^{-1} m^{-1}) than the others (second highest intensity is only 4.6 kg s^{-1} m^{-1}, and most points range from 0.03 to 0.6 kg s^{-1} m^{-1}). A marked difference between pre- and post-1994 floods is also clearly evident. Two aspects can be pointed out comparing the pre- to the post-1994 data: first, the overall higher bed-load rates during post-1994 events for similar liquid discharges, and their much steeper curve for flow rates between 3 and 4 m^3 $s^{-1}$where they display a single relationship, yet poorly represented. As to the former point, bed-load rates at 3.5 $m^3 s^{-1}$ equals 0.27 kg s^{-1} m^{-1} for pre-94 period, whilst it turns out to be 2.06 kg s^{-1} m^{-1} for the post-94 events. Thus, as already mentioned, the September 1994 flood represents a definite moment of change for the channel as to its morphology and sediment availability (Lenzi *et al.*, 2004).

Bed-load transport temporal trends and sediment supply conditions

Analyzing temporal trends of the hydrological and sedimentological data of floods recorded in the Rio Cordon between 1987 and 2004, limited and unlimited sediments supply periods are clearly evident, separated by the September 1994 event. During this extreme event, the channel bed was the main source of sediment for bed-load transport (Lenzi *et al.*, 2003) mostly because such a large discharge was able to destroy the streambed armour layer formed over the years. Fine and medium size sediments eroded from the hillslopes were stored in the stream network as the flood waned and were removed and transported downstream by subsequently ordinary floods.

The effective runoff (R_e), determined for each flood as the hydrograph volume exceeding the detected threshold discharges (Q_{cr1-2}) from the beginning to the end of the bed-load transport, provides a means to normalize total bed-load volumes (*BL*) and thus allows to infer temporal trends in the bed-load yields. The BL/R_e ratio calculated for each flood exhibits two decreasing trends over the 1986-1993 and 1995-2004 periods, and its value for the September 1994 flood is more than one order of magnitude larger than in the other floods. Before 1994, the ratio was always below 1, whereas afterward it is mostly above 1, as a response to such a destabilizing event. The decreasing trends can be ascribed to the flushing of sediment from the streambed and other active sources by "ordinary" events.

Travel length of marked bed particles

From a field observations carried out on the displacement length of various sizes of ($32 < D_i < 512$ mm) bed particles during individual flood events in the 1993–1994 and 1996–1998 periods, it was observed that the total displacement length (L_i) depends on the degree of mobilization of the individual fractions of the bed surface. L_i is independent of D_i for smaller, fully mobile grain sizes and decreases rapidly with D_i for larger fractions in a state of partial transport (Lenzi, 2004). Sustained selective transport without a supply of sediment from upstream leads to the development of a stable coarse armoured surface through progressive winnowing of finer material from the bed surface. With supply unlimited conditions for transport, both the occurrence of extreme events and the duration of a sequences of ordinary floods play an important role in the degree of mobilization of the individual fractions of the bed (Lenzi, 2004). Near-equimobility conditions from pebbles to small boulders (32-256 mm, i.e. up to the $D_{76}$of the bed surface grain size distribution) were established for the 1994 event (Q_p=10.4 m^{3}s^{-1}, $R.I.$ around 50 yr) while selective entrainment occurred for larger clast size (up to 512 mm). This might indicate that, during this event, a transport stage between a well-developed Phase II and the beginning of Phase III transport (Ashworth & Ferguson, 1989; Warburton, 1992) was reached. This hypothesis is supported by the findings of Lenzi *et al*. (2004), who highlighted that the very high bed-load rates of the September 1994 flood are much higher respect to the second largest event (the 1998 flood, Q_p = 4.7 m^{3}s^{-1}, $R.I.$ about 5 yr; equimobility only for size classes up to the D_{40}).

EFFECTIVE DISCHARGES

The availability of hourly values of bed-load transport in the Rio Cordon for a very large range of water discharges, made it possible to use both the "traditional" bed-load rating curve approach and the actual bed-load transport rates for each flow class, using the average values (Mao *et al.*, 2005). The effective discharge provided by the traditional Wolman & Miller (1960) approach, involving the use of a power sediment rating curve and a lognormal flow frequency curve, can be considered first. The product of the two curves starts at 1.4 $\mathrm{m^3s^{-1}}$, which is the minimum value for the application of the rating curve, and reaches its peak at a water discharge of 2.45 $\mathrm{m^3s^{-1}}$. This value ($R.I.$=1.72 yr, equalled or exceeded on average 7 hours per year or 0.02% of the time), therefore represents the bed-load effective discharge, and is very close to the estimated bankfull discharge of 2.3 $\mathrm{m^3s^{-1}}$. Using the measured bed-load transport rates and the empirical flow frequencies, grouped in classes of 0.1 $\mathrm{m^3s^{-1}}$, the effective discharge distribution turns out to be much more irregular and to have a very jagged pattern that prevents the identification of a representative peak. The actual maximum occurs at Q = 2.65 $\mathrm{m^3s^{-1}}$, similar to the previously obtained 2.45 $\mathrm{m^3s^{-1}}$. Nevertheless, three other high values, very close to the absolute maximum, are reached at 1.65, 3.45 and 3.95 $\mathrm{m^3s^{-1}}$, thus questioning the appropriateness of a unique effective discharge. As pointed out by Crowder & Knapp (2005), the evaluation of the effective discharge is significantly influenced by the kind of sediment data used (i.e. rating curve *vs* empirical data). The type of flow frequency curve (empirical *vs* fitted distribution) and its class intervals also affect the effective discharge determination.

TOTAL SEDIMENT YIELD

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 suspended sediment concentration ($S.S.C.$) was used to cover periods characterised by flows lower than a certain discharge threshold (i.e. 0.8 $\mathrm{m^3s^{-1}}$). Different relationships were obtained for summer-autumn floods and for spring snowmelt runoff. Analyzing the annual budgets of the suspended solid transport for the whole period, it appears that 76% of the total sediment load which occurred over the whole period 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% (Lenzi *et al.*, 2003).

Such a result confirms the strong link between suspended load and the availability of sediment sources. During the first part of the 14 September 1994 hydrograph event, suspended transport was the dominant process, instead of the second part, when suspended sediment was still important but the massive water discharge led to very large bed-load rates. Overall, suspended load accounts for about 61% by weight of the total sediment yield. In fact, as to report considering bed-load transport, suspended sediment yield are essentially conditioning by this extreme event, and post-1994 average annual suspended load is higher than for the preceding events.

Averaging the 18 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 post-1994 period featuring high annual loads (130.6 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 (Lenzi *et al*., 2003).

CONCLUSIONS

This summary emphasises the crucial connection between channel processes and sediment sources in mountain rivers. The key issue is the degree to which hillslopes and stream channel are coupled along with the stability of bed armouring, both of which significantly depends on the recurrence interval of flood events. In small mountain basins, the channel may remain decoupled and armoured for many years, until a low-frequency, high-magnitude event (like the 1994 flood in the Rio Cordon) remove the coarse surface layer, abruptly increasing sediment supply thus leading to higher sediment transport rates and mean annual yields.

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