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Bedload Dynamics in Steep Mountain Rivers: Insights from the Rio Cordon Experimental Station (Italian Alps)

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Abstract

Quantification of bedload transport in high-gradient mountain streams is of major importance, but field data necessary to test transport models are scarce. In the present work, we describe the experimental station for the monitoring of water and sediment fluxes built in 1986 on the Rio Cordon (Eastern Italian Alps), a small step-pool channel. The measuring station consists of an inclined frame that separates (at 20 mm truncation) fine and coarse sediments, the accumulations of which are continuously measured by pressure transducers cells and ultrasonic sensors, respectively. Suspended sediment is measured by two turbidometers. The acquired two decadal dataset, which comprises a high-magnitude/low-recurrence flood event, has allowed a magnitude-frequency analysis of bedload rates and volumes, as well as evaluation of incipient motion and of effective discharge for sediment transport. In addition, the integration between the sediment transport dataset and the repeated surveys of sediment sources and of channel changes has permitted to assess the geomorphic effectiveness of different flood events.

Introduction

The quantification of bedload transport in steep mountain streams is of major importance for planning hazard mitigation, for predicting reservoir sedimentation and for understanding morphodynamics of higher-order channels. However, poorly sorted mountain rivers may require high, infrequent discharges for the mobilization of the coarsest clast size so that, annually, only a portion of finer (gravel and cobble) particles is likely to be entrained (Wohl, 2000).

The monitoring activity of bedload transport in steep, small (<10 km^2) mountain catchments poses problems that are very complex due to the impulsive, high-energy nature of this process, where intense sediment transport can even lead to non-newtonian flows (hyper-concentrated flows or debris flood). The short duration and relatively low frequency of occurrence of the events require the implementation of robust and reliable systems for performing direct field observation. Indeed, monitoring activities carried out through permanently installed devices are very costly. However, these experimental sites become of extreme value when long-term series of data are eventually produced, thus allowing statistically significant analysis and experience-based predictions (Mao et al., 2006).

Experimental measuring stations thus represent precious tools for the scientific community as well as for the agencies dealing with torrent control and land use planning.

This paper presents the experimental facility of the Rio Cordon (Eastern Italian Alps), summarizes the results gained during 20 yr of operation, and discusses costs and drawbacks of the deployed technology.

Rio Cordon basin and channel

The Rio Cordon is a boulder-bed, step-pool stream draining an area of 5 km^2 (Fig. 1; Tab. 1). The hillslopes are very steep (mean gradient 52 %) and, due to its high elevation, forests cover only the lower 7% of the catchment. Alpine grasslands dominate (61%), but shrubs are relatively widespread (18%). Fourteen percent of the catchment area consists of bare land (scree and rocky cliffs). The lithology mainly consists of dolomites, volcaniclastic conglomerates and tuff sandstones. Quaternary fluvioglacial and colluvial deposits are also very common. Active sediment sources, which are mainly represented by bare slopes, shallow landslides, eroded stream banks and minor debris flow channels, cover 5.2% of basin area. However, about 50% of the sediment source areas lie upstream of a low-gradient belt located in the middle part of the basin. Such a geological “sill” promotes sediment deposition, thus limiting sediment supply from the upper part of the basin.

The Rio Cordon mean channel slope is 13.6% but the longitudinal channel profile displays an alternation of high-gradient and low-gradient stretches. The Rio Cordon is a boulder bed channel featuring a step-pool morphology (Fig. 1), giving a high stability to the bed channel for flood events with recurrence intervals (R.I.) lower than 30-40 years (Lenzi, 2001). The average bed surface grain size distribution is characterized by D_{50} = 0.12 m and D_{84}=0.36 m. The mean grain size (D_m) is 0.11 m. The grain size distribution was derived from five grid-by-number pebble counts, carried out within a upstream of the measuring station. At each sampling site, 110 to 260 clasts were measured with no distinction based on morphological units. The entire sample (999 elements) was used to derive the surface grain size distribution, with a lower truncation of 4 mm (Mao and Lenzi, 2006). In order to determine the grain size distribution of the subsurface bed material, eight sites were sampled adopting the mass criteria proposed by Church et al. (1987) after removing the surface layer to a depth approximating the D_{90} of each site (Lenzi, 2004). Samples weight varied from 600 to 850 kg, with a maximum particle size between 120 and 320 mm. The subsurface grain size distribution is substantially finer than at the surface (D_{50ss}=0.038 m and D_{84ss}=0.125 m), thus demonstrating a strong degree of surface armouring (D_{50}/D_{50ss} ~ 3).

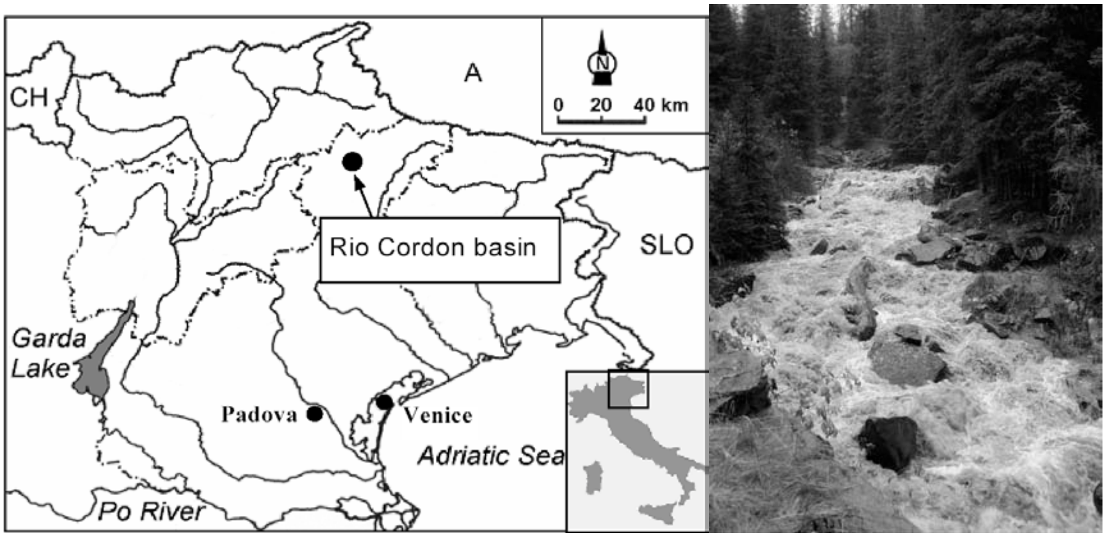

Figure 1. Rio Cordon location and view of main channel at approximately bankfull stage (Q=2.3 m3s-1).

Table 1. Main characteristics of the Rio Cordon basin and channel.

Basin area	(km^2)	5.0
Minimum elevation	(m.a.s.l.)	1763
Maximum elevation	(m.a.s.l.)	2748
Mean hillslope gradient	(%)	52
Mean width of the main channel	(m)	5.7
Mean gradient of the channel upstream of the station	(%)	13.6
Mean annual precipitation	(mm)	1100
Maximum flow discharge	($m^3 s^{-1}$)	10.4
Mean flow discharge	($m^3 s^{-1}$)	0.26

Rio Cordon monitoring facilities

Facilities for monitoring water discharge, suspended sediment and bedload transport at the Rio Cordon experimental station (built in 1995-1996) have been described in detail in previous papers (Fattorelli et al., 1988; Lenzi et al., 1999; Lenzi et al., 2004). Bedload measurements are taken by separating coarse grains (minimum diameter 20 mm) 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 to the stream (Fig. 2 and 3). A scaled physical model of the facility had previously been built at the Hydraulic Laboratory of the University of Florence (Italy) to study the hydraulic behavior of its channel system. The model was realized at a 1:25 scale, and different structural solutions for the inlet and outlet channels, frame dimensions and slopes were tested. The channels of the station were designed for a maximum discharge of 25 m^3s^{-1}.

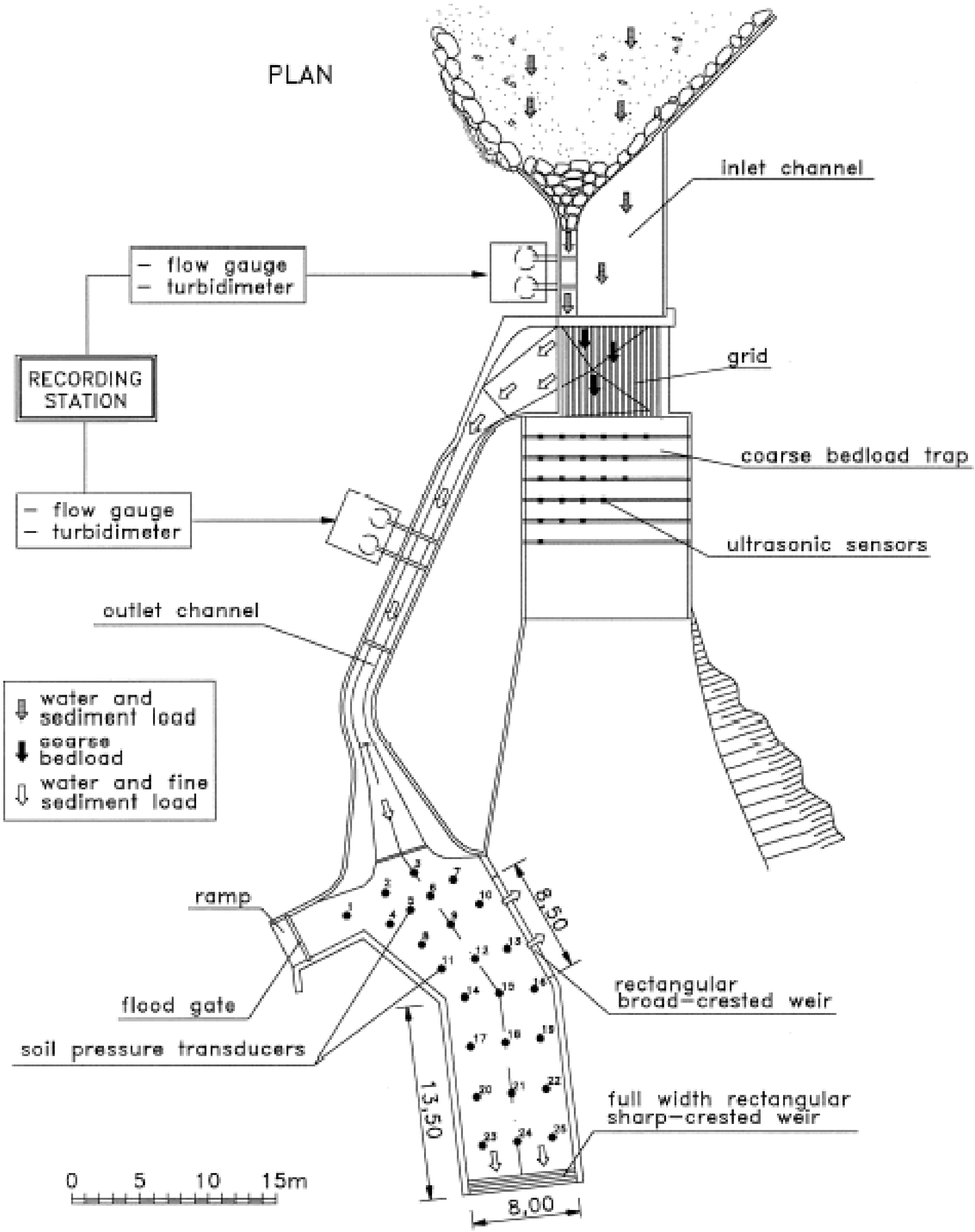

Figure 2. Plan view of the Rio Cordon measuring station.

A frame was built in 1996 over the bedload trap in order to obtain a fixed grid of ultrasonic sensors (two steel cables supported by two steel beams for each line of sensor, Fig. 3c and 3d) instead of a line of sensors moving back and forth on an over-head crane, as used during 1985-1996. Twenty-four ultrasonic sensors are installed. The first upstream three lines of sensors are spaced at 1.5 m intervals in downstream and in cross-stream directions, the last two lines of sensors are spaced at 1.5 m intervals in a cross-stream direction and at 2 m in a downstream direction (Fig. 3c and 3d). This setup ensures a detailed survey of the depositing of coarse bedload during a flood-event. In fact, all ultrasonic sensors can survey the growing bedload volume deposit simultaneously and continuously at 5 min intervals.

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 (area of about 205 m2 and depth of 3.5 m) located downstream of the outlet flume (Fig. 3b). The pressure transducers, installed in 1995, consist of completely waterproof cells made like a stainless steel disk (diameter 140 mm; thickness 25 mm). Each transducer measures the weight affecting the sensitive surface of the disk. A linear relation occurs between the output signal of the transducers at the time t and the vertical height of the water column and height of sediment on the transducer. The calibration was conducted (in 1995) in the laboratory by using a circular Plexiglas pipe (2.1 m height and 0.4 m in diameter) and the sediment collected from the settling basin after a flood-event. The sensitivity of the transducer, in terms of detectable sediment height variation on the disk, is about 10 mm if when water pressure is constant. A test on the accuracy of the linear relation showed a maximum error between the computed and the measured height of the sediments of about 13%. The practical application of the laboratory derived relation to the data obtained by the settling basin requires contemporaneous measurements of the output signal of the transducers (directly proportional to the total pressure on the disk) and the hydrostatic pressure at the bottom. The latter is subtracted from the total pressure to compute the effective weight of the sediment and thus the correct height. Field calibration of the pressure transducers was conducted during 1998 considering the increase of clear water depth without sediment supply and the increasing sediment load over the pressure transducer with constant water depth. Water level gauges are installed in the inlet and outlet channels and in the settling basin.

Suspended sediment is measured by a Partech SDM-10 and a Hach SS6 turbidometers. The Partech is an infrared absorption turbidometer installed in the outlet channel operating since the early years of station operation (Fig. 3f). The turbidometer Hach SS6 (Surface Scatter turbidometer) was installed in 1994 at the inlet channel (Fig. 2). The instrument continuously measures the light scattered by particles suspended in a sample fluid, pumped from the stream into the center of an inclined turbidometer body at a flow rate of 1 -2 liter/min. As the fluid spills over the top of the turbidometer body, a stable, flat surface of liquid forms and becomes the measuring surface. A high-intensity beam of light is directed to strike the surface of the liquid at an acute angle, is scattered by particles suspended in the sample and is detected by a photocell positioned directly over the point where the light enters the liquid. The instruments measure the turbidity as degrees of scattered light. Readings are given in terms of NTU (Nephelometric Turbidity Unit), and the relation between NTU and suspended sediment concentration (SSC) was calibrated through simultaneous flow samples and turbidometer measurements. Flow samples are obtained automatically using a Sigma pumping sampler; the sampling head is installed at a fixed location in the inlet channel. The sampler is set to automatically collect flow samples at a fixed time interval when a discharge threshold is exceeded. Furthermore, samples are collected manually during low flows and minor floods in selected verticals using a USDH48 bottle sampler. The bottle sampler is handled by a rod from the low bridges over the inlet (Fig. 3a) and outlet channels (Fig. 3f). Samples were collected manually also during a major September 1994 flood. Data from the automatic and manual samplers allow evaluation of average SSC. To detect possible errors in using turbidity records for estimating SSC (e.g., associated to mineralogy and particle size), turbiditimeter-derived SSC values were compared with flow samples collected during flood events (Lenzi and Marchi, 2000). Different turbidity response due to sediment mineralogy was not observed in samples collected at the Rio Cordon station, where suspended sediment lithology, an accumulation and averaging of upstream sources does not vary considerably among flood events (Lenzi and Marchi, 2000). As to the influence of particle size on NTU – SSC relationships, this became apparent in the Rio Cordon only during a very intense flood – possibly a hyperconcentrated flow at the peak – when coarse particles (sand and very fine gravel) were transported in suspension (Lenzi and Marchi, 2000). Other sensors for monitoring water temperature, pH and electric conductivity are also installed at the inlet channel.

Figure 3. Photos of the Rio Cordon measuring station: a) Downstream view of the bedload storage, the outlet flume and the two buildings hosting instrumentations and the emergency power system; b) Upstream view of the fine sediment settling basin; c) Downstream view of the separating grid, the bedload storage area and the cable frame which host the 24 ultrasonic sensors; d) Upstream view of the bedload storage area; e) Downstream view of the inlet channel; f) Downstream view of the outlet channel with the Partech SDM-10 light absorption turbidometer fixed under the bridge.

Bedload dynamics in the Rio Cordon

Magnitude-frequency analysis of bed-load intensity and volumes

From 1987 to 2006, twenty-four floods characterized by bedload transport (grain size greater than 20 mm) were recorded at the measuring station. In order to evaluate their frequency of occurrence, the return interval (R.I.) of each flood peak was estimated from values of annual maximum water discharge using a log-normal distribution. Likewise, return intervals of bedload volumes were estimated using the annual maximum volumes adopting a log-normal distribution, although bedload transport is not an independent of water discharge. Bearing in mind these limitations and uncertainties, the comparison of water and bedload R.I., it is evident that bedload volumes are higher after the 1994 flood for comparable water discharge frequencies (Fig. 4). The same result is also obtained when the return periods are calculated without the September 1994 data.

Indeed, 1994 appears to represent a threshold for bedload transport in the Rio Cordon basin. On September 14, 1994, a flood with a peak water discharge of 10.4 m3 s^{-1} and a hourly-averaged bed-load intensity of 225 m3 h^{-1}occurred. This event features a very short duration and a very high, infrequent peak flow rate (R.I. ≈ 70 yr), with a total bedload volume of 900 m3 (R.I. ≈ 35 yr). However, because the analysis is based on a 2 decadal dataset, the R.I. for the 1994 flood should be considered as indicative only. In addition, recurrence intervals derived from regional rainfall data are not reliable due to their marked spatial variability and to the convective nature of the 1994 storm (maximum rainfall rates were 7.2 mm for 5 min, 16.4 mm for 15 min and 25.3 mm for 30 min). The September 1994 flood, the largest recorded during the study period, altered the stream geometry (Lenzi, 2001) and the sediment-supply characteristics of the basin (Lenzi et al., 2004). During this event the channel bed was the main source of sediment for bedload transport mostly because such a large discharge was able to destroy the streambed armour layer formed over the years. Also, during the September 1994 flood, old sediment sources were reactivated and new ones were formed (Lenzi et al., 2004). Fine- and medium-size sediments eroded from the hillslopes were stored in the stream network and were then removed and transported downstream by later ordinary floods. The 1994 flood remarkably changed the step-pool morphology of the Rio Cordon by the contemporary effect of step disruption and pool burying. The subsequent "ordinary" foods slowly re-established the morphological features by an effect of pool scouring supported by a low sediment supply to the stream network (Lenzi, 2001).

Sediment volumes higher than those mobilized during the 1994 flood are unlikely to occur in the Rio Cordon as bedload under Newtonian flow conditions. In fact, during that flood the suspended sediment transport peaked at a value of 58 g l^{-1} and the bedload rate was so intense that the event approached hyper-concentrated flow conditions. Indeed, a visual observation of the event (taped by a video camera) confirms that a hyper-concentrated flow was likely reached. An even more intense, infrequent event (e.g., R.I. > 100 yr) would probably occur as a debris flow. Field evidence along the main channel and on adjacent terraces, such as lobes and levees with large boulders, suggest that debris flows have occurred in the recent past along the Rio Cordon (Mao et al., 2006).

An important new sediment source in the basin formed on 11 May, 2001, simultaneous to a minor flood event in the main channel. Soil saturation mobilized a shallow landslide which then turned into a mud flow moving along a small tributary (Lenzi et al., 2004). A debris fan (volume 4,000 m^3) formed at the confluence with the Rio Cordon, thus feeding the main channel with medium and fine sediment. The quasi-unlimited sediment supply conditions allowed the ordinary snowmelt flood (R.I. ≈ 1.2 yr) to transport 80 m^3 (R.I. ≈ 4 yr) of sediments to the measuring station (Fig. 4).

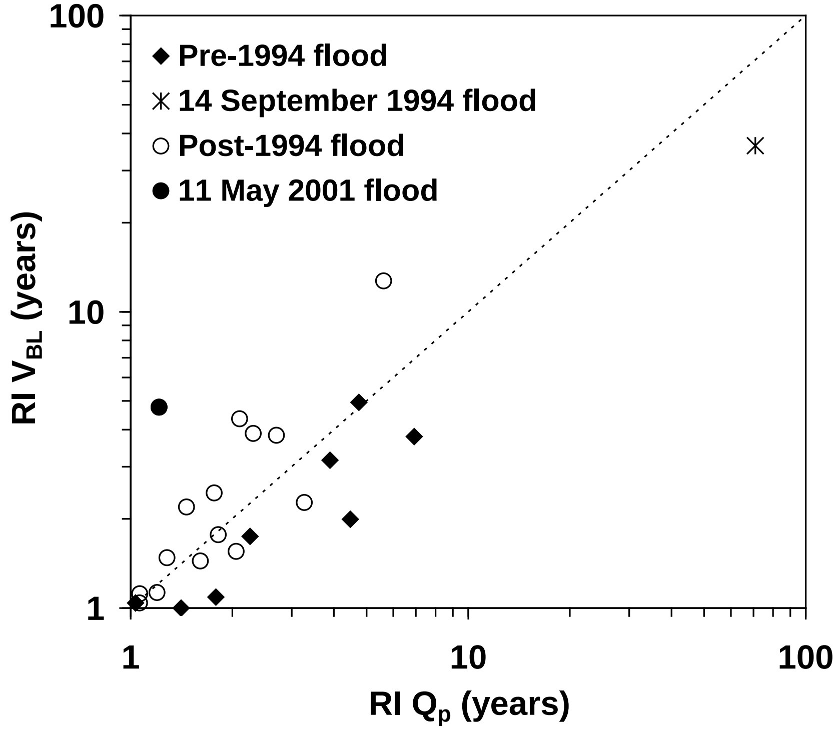

Figure 4. Comparison between total bed load volumes (RI VBL) of each recorded flood event since 1987 to 2006 and between recurrence intervals for liquid peak discharge (RI Qp).

Bedload rating curve

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 discharge averaged over the antecedent 60 minutes throughout each flood event. The bed-load intensity data was grouped into three categories: September 1994 event, pre-1994 and post-1994 flood events (Fig. 5). The September 1994 flood displays much higher values (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^3s^{-1} were 0.27 kg s^{-1} m^{-1} for pre-1994 period, but 2.06 kg s^{-1} m^{-1} for the post-1994 events (Fig. 5). Thus, the September 1994 flood represents a definite moment of change for the channel as to its morphology and sediment availability (Lenzi et al., 2004).

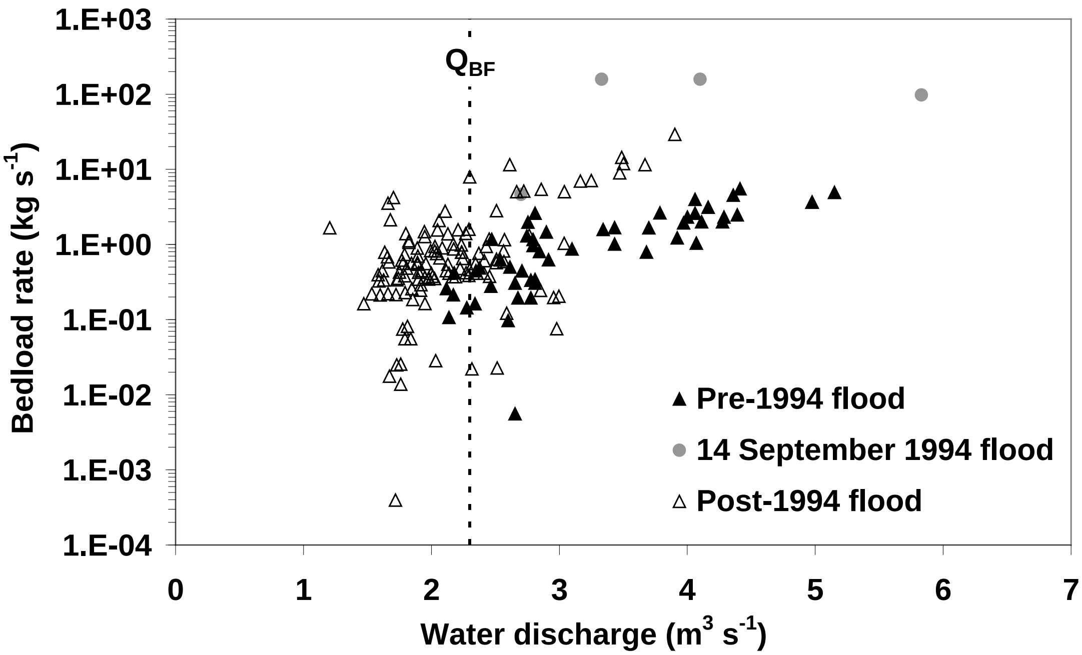

Figure 5. Semi-log plot of bed load rate vs water discharge of pre-1994 events, 1994 flood and post-1994 events. The bankfull discharge is denoted by the vertical dashed line.

Bedload incipient motion and transport conditions

Two methods have been used to determine threshold of motion in the Rio Cordon: the displacement of marked clasts and the flow competence approach which uses the largest grain size diameter transported by each flood event (Lenzi, 2004; Lenzi et al. 2006a).

In May 1993, two groups of 430 natural pebbles, cobbles, and boulders (32 mm < D < 512 mm) were painted and placed across two reaches upstream of the station, in transverse rows 1 to 2 m apart (Lenzi, 2004). The movement of the marked clasts was mapped during consecutive surveys from July 1993 to October 1994, thus including the effects of the September 1994 flood. After this large flood, two similar groups of 430 tracers were laid out on the two cross sections, and their displacement was mapped between May 1996 and October 1998 (Lenzi, 2004). As to the competence approach, it involves the analysis of the largest bedload particles transported during flow events (Andrews, 1983), i.e., the maximum clast diameter transported during a flood is associated with the corresponding flood peak discharge. In the Rio Cordon, the grain size distribution of the transported sediments is available for 15 flood events (Lenzi et al., 2006a).

The values of critical shear stresses evaluated using the marked particles and the competence methods were found to be higher than previously reported for gravel-bed rivers. However, examining the relationship between the critical Shields parameter τ^*_{ci} and the relative sediment size D_i/D_x, it is in good agreement with both D_{50}-based functions (Ashworth and Ferguson, 1989; Marion and Weirich, 2003) and with Petit's (1994) formula that uses D_{90}.

The results (Mao and Lenzi, 2007) also suggest that size-selective bedload transport occur in boulder-bed channels for moderate floods (R.I. < 5 years) and the approaching of equal-mobile conditions during low frequency, major floods, in accordance with previous field (Church et al., 1991;

Kuhnle, 1992; Wathen et al., 1995) and flume observations (Wilcock and McArdell, 1993). Equal-mobility transport seems to occur when water discharge is 3.9 larger the incipient discharge for a given size class, and, in terms of shear stress, when this is 1.45 larger the critical shear stress of each sediment size. A similar result has been previously found in flume experiments (Wilcock and McArdell, 1993) and natural gravel-bed rivers (Church and Hassan, 2002).

Bedload effective discharge and transport duration

In the Rio Cordon, the effective discharge was calculated (Lenzi et al., 2006b) using both the "traditional" (best-fit flow frequency distribution and a sediment rating curve as originally proposed by Wolman and Miller, 1960) and the "mean" approach, involving actual frequency of occurrence and the average *measured* sediment rates for each flow class. Bedload effective discharge was found to be slightly higher, yet comparable, to the bankfull discharge. However, the effective discharge curve for bedload transport obtained by the "mean" approach shows a marked jagged pattern and a single peak is thus thought to be poorly representative. The results suggests that two discharge ranges may exert geomorphological impacts on mountain rivers: a) relatively frequent floods (R.I. ~ 1.5 – 3 yr) responsible for maintaining the channel form in terms of pool depth, and step-pool steepness; and b) more infrequent, higher floods (R.I. ~ 30 – 50 yr) responsible for macro-scale channel shaping in terms of major step destruction-creation, channel width adjustments and plan-form changes.

In high-gradient, coarse-grained streams, several factors make the determination of bankfull stage more difficult than in gravel- or sandbed rivers. Channels adjustments to water and sediment flows are limited by bedrock outcrops and/or large immobile boulders. Furthermore, the adjacent floodplains are often very small or completely absent due to channel confinement, and steep streams are usually sediment supply-limited and their relaxation times after channel-changing events can be very high (i.e. decades). In the Rio Cordon, bankfull stage was first identified at several cross sections using both the lower limit of vegetation and changes in sediment size on small lateral bars (Lenzi et al., 2006), and then it was directly observed during several events (Fig. 1) associated with a measured discharge at the station of about 2.3 m3s-1, which corresponds to an estimated recurrence interval of 1.6 yr.

Flows up to the bankfull stage transport the 97.7% of the sediment in suspension, but only 38.3% of the longterm bedload yield. The recurrence interval of the bankfull discharge approximates 1.6 year, and is exceeded 9.15 h/year (0.025% of the time). The incipient motion discharge for the D_{50} is lower than the bankfull and bedload effective discharge, and is exceeded only 2.4 day/yr, whereas the entrainment discharge for D_{84} (and D_{90}) is higher, with a duration of 1.4 and 0.2 h/yr, respectively.

Maintenance costs and drawbacks of the Rio Cordon facility

The station generally operates 40-45 weeks per year – i.e. in winter is closed due to the deep snowpack and the irrelevant flows – and, on average, the ordinary maintenance requires 250-300 hours per year. The station is normally visited by technicians once a week, but all the data collected are daily radio transmitted to the Arabba Avalance Center (public agency run by the Veneto Region). The ordinary weekly operations consist of sensor check-up (of those giving erroneous data during the previous week), manual cleaning of turbidometers, manual pH and conductivity measurements, manual sampling of suspended sediment transport, maintenance of other complementary instruments (hydrometer, hygrometer, pluviometer) whose data are registered on paper. The good accessibility to the station, i.e. paved road, is crucial to guarantee both ordinary maintenance of the instrumentations, and a quick access during the – typically short – bedload transporting events, in order to directly observe their phenomenology.

Although the station has overall fulfilled its required tasks, there are several aspects that could be ameliorated to allow more accurate bedload measurements. The separating grid should be longer than the current 8.5 m, both to avoid that a fraction of the water flow "bouncing" on it would splash on the storage area below at flood flows (Fig. 3d), and to carry out a better sieving action on sediment particles. At present, in fact, a few fine (< 20 mm) particles are found in the storage area where only coarser clasts are to be deposited. The grid slope (60% and 27% in the longitudinal and transversal direction, respectively) seems to work reasonably well during both low and high discharge. Deposition of sediment was never observed on the grid apart from final stage of the 1994 flood, which completely filled the storage area. The pressure transducers placed underneath the fine sediments retention basin do not always work as expected, and therefore the exact quantification of the transported volume of particles (D < 20 mm) rely on the topographical survey of accumulated sediment only.

Fluctuations in the volume data produced by the ultrasonic sensors placed above the bedload storage area (Fig. 3d) are partly caused by wind. A simple shielding structure over and beside the sensor would avoid swinging and protect them from adverse weather conditions. The most expensive maintenance is often related to these sensors. The roof above the storage area could be an appropriate location for a fixed videocamera and a spotlight in order to continuously record the formation of the sediment mound, thus allowing to infer the transported sediment size at each flood stage. The videocamera is to be programmed to operate when water discharge exceeds the same threshold set for ultrasonic sensor activation. Also, at present, the bottom of the bedload storage area is not cemented (Fig. 3c), whereas its lining with concrete would lead to more precise ultrasonic measurements and a simpler post-flood bedload removal.

The rectangular sharp-crested weir located at the downstream end of the fine sediment retention basin is at present too wide to allow accurate measurements of flow rates $< 0.1\ m^3\ s^{-1}$. A V-shaped weir in conjunction to the rectangular weir would permit a more precise quantification of low flows. In order to increase the accuracy of discharge measurements during high flows, the inlet channel upstream of the station (Fig. 3e) should be extended for about 5 m to avoid the formation of standing waves disturbing the flow gauging system.

Finally, the Rio Cordon facility provides an ideal means for validating surrogate methods for bedload measurements in steep channels. For example, in the cemented inlet channel, piezoelectric impact sensors such as those installed in several Swiss mountain torrents (Rickenmann and McArdell, in press) could be installed, as well as other passive acoustic devices and magnetic methods (this book). A Birkbeck bedload slot-sampling system - like the one operating in the Nahal Eshtemoa (Powell et al., 2001) - could possibly be installed in the narrow cemented outlet channel, in order to measure transport rates of fine sediments, which could then be compared with the total fine sediment accumulated in the retention basin.

Final Remarks

The Rio Cordon measuring facility has provided excellent data and valuable insights into the bedload dynamics of steep streams throughout its 20 years of operative period, thanks to the tight collaboration between the Arabba Avalanche Center (Veneto Region) and the Department Land and Agroforest Environments (University of Padova). However, the maintenance costs of the station are not trivial and may impact its future "vitality". At the same time, ameliorations of the present instrumentations and installation with novel technology would make the station and ideal location for calibrating surrogate techniques for bedload monitoring.

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