



Effective discharge for sediment transport in a mountain river: Computational approaches and geomorphic effectiveness

M.A. Lenzi ^{*}, L. Mao ¹, F. Comiti ¹

*Department of Land and Agro-Forest Environments, University of Padova, Agripolis,
Viale dell' Università 16, 35020 Legnaro, Padova, Italy*

Received 18 May 2005; revised 30 September 2005; accepted 27 October 2005

Abstract

Dominant, effective, bankfull and channel-forming discharges are different concept-based flows, often applied as design parameters in river management and restoration. In order to achieve a better understanding of channel-forming conditions in high-gradient, boulder-bed streams, the long-term sediment loads data obtained from the Rio Cordon (Italian Alps) measuring station have been analysed. The effective discharge (Q_e , calculated using both Wolman and Miller's method and the so-called 'mean' approach) for bedload transport proves to be more appropriate than that determined for the suspended sediment load in describing the channel formation and maintenance for this type of channels. The analysis demonstrates that Q_e is strongly influenced by the number of flow classes, the fraction of transported sediments and the methodology used in its computation. The result questions the appropriateness in considering Q_e as an unique value, and also suggests the possible definition of two dominant discharge ranges for steep mountain rivers: (a) a relatively frequent flow range responsible for maintaining channel form; and (b) a more infrequent high flow range responsible for macro-scale channel shaping.

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Keywords: Effective discharge; Bankfull discharge; Bedload transport; Magnitude–frequency analysis; Duration curve; High-gradient streams

1. Introduction

Alluvial rivers adjust their channel and floodplain dimensions depending on the range of flows which are

capable of mobilizing sediment from the bed and banks, and of transporting sediments delivered from upstream reaches. Since the early work by Schaffernak (1922), many authors have proposed that a single, representative discharge may be used to define the channel geometry that, in the long-term, could be considered stable. The design of a channel for environmental enhancement or ecological restoration of rivers requires the application of a proper water discharge considered responsible of long-term channel stability (Shields et al., 2003). A stable stream

^{*} Corresponding author. Tel.: +39 49 8272675; fax: +39 49 8272686.

E-mail addresses: marioaristide.lenzi@unipd.it (M.A. Lenzi), luca.mao@unipd.it (L. Mao), francesco.comiti@unipd.it (F. Comiti).

¹ Tel.: +39 49 8272695; fax: +39 49 8272686.

Nomenclature

D	grain size for which $i\%$ of the grains are finer, m		bedload rating curve and a lognormal flow frequency distribution ('traditional' approach), $\text{m}^3 \text{s}^{-1}$
E_b	effective discharge curve for bedload transport		
E_s	effective discharge curve for suspended sediment transport	Q_{eS}	effective discharge for suspended sediment transport, $\text{m}^3 \text{s}^{-1}$
f	flow frequency, %	Q_{eSMM}	effective discharge calculated using measured suspended sediment rates and measured flow frequencies ('mean' approach), $\text{m}^3 \text{s}^{-1}$
Q	water discharge, $\text{m}^3 \text{s}^{-1}$		
Q_{bf}	field-identified bankfull discharge, $\text{m}^3 \text{s}^{-1}$	Q_{eSRL}	effective discharge calculated using a suspended sediment load rating curve and a lognormal flow frequency distribution ('traditional' approach), $\text{m}^3 \text{s}^{-1}$
Q_{ci}	critical water discharge associated to the entrainment of D_i particles, $\text{m}^3 \text{s}^{-1}$	Q_{ri}	water discharge for a specified recurrence interval, $\text{m}^3 \text{s}^{-1}$
Q_{dom}	dominant discharge, $\text{m}^3 \text{s}^{-1}$	Q_{sb}	bedload rate, Kg s^{-1}
Q_e	effective discharge, $\text{m}^3 \text{s}^{-1}$	Q_{ss}	suspended sediment rate, Kg s^{-1}
Q_{eB}	effective discharge for bedload transport, $\text{m}^3 \text{s}^{-1}$	RI	recurrence interval, year
Q_{eBMM}	effective discharge calculated using measured bedload rates and measured flow frequencies ('mean' approach), $\text{m}^3 \text{s}^{-1}$	SSC	suspended sediment concentration, g l^{-1}
Q_{eBRL}	effective discharge calculated using a		

configuration is essentially dependent on the channel ability to convey the whole amount of sediments supplied from above, with neither net erosion nor aggradation of streambed and banks.

This channel-forming, also named dominant discharge (Q_{dom}) is the discharge, which a channel should be designed to convey. Given the complexity of its quantification, such a discharge has been associated with different concepts by different researchers, including the field-identified bankfull discharge Q_{bf} (Wolman and Leopold, 1957; Leopold et al., 1964), a specified recurrence interval discharge Q_{ri} (Dury et al., 1963; Williams, 1978) and the effective discharge for sediment transport Q_e (Wolman and Miller, 1960; Andrews, 1980). Such a variety of approaches have led to some confusion about both terminology and understanding of the fundamental processes involved.

Bankfull discharge (Q_{bf}) is the maximum discharge that a channel can convey without overflowing onto its floodplain, and is considered to have morphological significance because it represents the boundary between channel and floodplain formation

processes. It is commonly determined by identifying the bankfull stage and then determining the associated discharge. Among the most common indicators of bankfull stage are: the elevation of the active floodplain (Wolman and Leopold, 1957); the maximum elevation of channel bars (Wolman and Leopold, 1957); the height of the lower limit of perennial vegetation (Schumm, 1960), and changes in the vegetation composition and distribution (Leopold, 1994). A more analytical and geomorphological-based approach, assumes the bankfull stage to correspond to the elevation at which the width/depth ratio of a typical cross-section is at a minimum (Pickup and Warner, 1976). However, none of these field methods can be used alone to obtain reliable results (Williams, 1978).

Owing to the difficulties associated with identifying Q_{bf} from field evidence, many researchers have related the bankfull discharge to a specific recurrence interval discharge (Q_{ri}) by analysing at-equilibrium natural channels where the bankfull stage could be easily identified and stream gauges were located in the vicinity. Under these conditions, Q_{bf} is assumed to be

the channel-forming discharge, and most of the literature uses the two terms interchangeably. Based on the annual maximum flow series, the recurrence interval (RI) of Q_{bf} often approximates the 1.5-year flow event (Dury, 1977; Leopold et al., 1964; Dunne and Leopold, 1978; Williams, 1978; Leopold, 1994) although substantial variations around this average value have been noted (Pickup and Warner, 1976; Nash, 1994). Williams (1978) showed that in 35 rivers in the USA the RI associated with the Q_{bf} varied between 1 and 32 years, and that only about a third of the rivers had a bankfull recurrence interval between 1 and 5 years.

The effective discharge (Q_e) was defined as the flow rate that is most effective in the long-term transport of sediment (Wolman and Miller, 1960), thus as the increment of discharge that transports the greatest proportion of the annual sediment load over a period of many years (Andrews, 1980). Q_e incorporates the principle put forward by Wolman and Miller (1960) stating that the channel-forming discharge is a function of both the magnitude of sediment-transporting events and their frequency of occurrence. They also suggested that it could be identified as the point of maximum of the function resulting by the product of the flow frequency curve and the sediment transport rating curve.

Since its earlier definition, the return interval of the effective discharge has been quantified to be between 1 and 2 years (Wolman and Miller, 1960). This finding is supported by further works (i.e. Leopold et al., 1964; Dury, 1973; Andrews, 1980; Andrews and Nankervis, 1995; Leopold, 1994; Rosgen, 1996), which show that Q_e corresponds to the Q_{bf} . However, other studies (Benson and Thomas, 1966; Pickup and Warner, 1976; Ashmore and Day, 1988; Nash, 1994; Hey, 1998) suggest a limitation in the effective-bankfull discharge identity. $Q_e - Q_{bf}$ deviations are probably due to the sediment fraction considered in the effective discharge calculation (Ashmore and Day, 1988; Nash, 1994; Knighton, 1998) and to the wide variation of bankfull recurrence interval (Williams, 1978).

Wolman and Miller (1960) originally determined Q_e from the suspended sediment rating curve, like many subsequent authors (Nolan et al., 1987; McKee et al., 2002; Simon et al., 2004), although other works start from the recognition that the channel form in gravel-bed rivers is fundamentally determined by

the coarser fraction of the sediment load, and therefore, Q_e has to be calculated using the bedload discharge (Leopold, 1992; Nash, 1994; Whiting et al., 1999; Emmett and Wolman, 2001). Bedload transport is the main geomorphologic factor in streams having coarse, well-sorted bed sediments, even though quantitatively this can be lower than suspended sediment transport (Lenzi et al., 2003). However, bedload is more expensive and difficult to measure rather than suspended sediment transport, hence in the few papers dealing with bedload effective discharge, empirical formulae (Andrews, 1980; Torizzo and Pitlick, 2004) or, at most, bedload rating curves have been used (Whiting et al., 1999; Emmett and Wolman, 2001). Several studies have been criticized for using this approach (see Dury, 1973; Carling, 1988; Newson, 1980), because treating sediment transport as a continuous function of water discharge does not consider that it can increase dramatically when some discharge thresholds are passed (Nash, 1994). Such a problem is amplified in high-gradient streams, where bedload transport is extremely impulsive and pulsating (i.e. Blizard and Wohl, 1998), and where the long-term phases of sediment supply conditions (Lenzi et al., 2004) challenge the use of a simple rating curve. In their pioneering work, Wolman and Miller (1960) pointed out that the magnitude–frequency determination of effective discharge is applicable in sand-bed rivers (low sediment entrainment threshold) with a humid/sub-humid temperate climate and well-vegetated catchments (Werritty, 1997).

Problems in Q_e determination also derive from the high degree of subjectivity in its calculation (Sichingabula, 1999; Biedenharn et al., 1999; Goodwin, 2004; Crowder and Knapp, 2005). In fact, even when a sediment rating curve is used instead of a predictive formula, there might be uncertainties as to the determination of the flow frequency distribution (Nash, 1994), in the quantification of the minimum length of the flow database (Crowder and Knapp, 2005), in the selection of the temporal discharge step (e.g. hourly vs daily values), and particularly in the choice of the number of flow classes used for the Q_e computation (Sichingabula, 1999; Crowder and Knapp, 2005).

Analysing the geomorphic impact of a low-frequency flood in the Hungry River, Phillips (2002) has recently criticized that a unique discharge can be

assumed as a channel-forming one. He hypothesized a bimodal dominant discharge, with a first, frequent discharge responsible for channel maintenance, and a second infrequent discharge responsible for shaping banks. Also Vogel et al. (2003) argue the meaning of Q_e as the discharge interval that maximizes the sediment transport effectiveness, pointing out that relatively rare flows, responsible for carrying most of the sediments over the long period, demonstrate an important morphological significance.

In this paper, the long-term (17 years) water discharge and suspended/bed-load transport data from the Rio Cordon (a steep, boulder-bed stream in the Italian Alps) are used in order to calculate its effective discharge.

The effective discharge is evaluated using both Wolman and Miller's method and an alternative approach involving measured sediment rates and actual flow frequency. The influence of flow class interval, computational methodology, and sediment transport fractions are explored. Finally, the relationship between bankfull and effective discharge and the geomorphological role of a high-magnitude, low-frequency flood are investigated.

2. The Rio Cordon basin and channel

The research was conducted in the Rio Cordon catchment (5 km²), a small stream in the Dolomites,

located in the Eastern Italian Alps (Fig. 1, Table 1). The bedrock geology consists of dolomite (which provides the highest relief in the catchment), volcanoclastic conglomerates and tuff sandstones. The main channel (13.6% as mean gradient) features cascade and step-pool reaches.

Its average bed surface grain size distribution is characterized (from grid-by-number pebble counts) by the following percentiles (in millimetre): $D_{10}=26$, $D_{16}=37$, $D_{50}=119$, $D_{84}=357$, $D_{90}=451$ (Mao, 2004). The mean diameter D_m is 112 mm. The standard deviation is 3.12, and the sorting coefficient is 1.60, thus indicating a poorly sorted mixture. The channel width during flood, in a typical cross-section just upstream of the station, varies from 5 to 6.7 m, depending on the discharge.

The instrumentation for monitoring water discharge, suspended sediment, and bedload transport at the Rio Cordon experimental station have been described in detail in previous papers (Lenzi et al., 1999; 2004). The measurements are taken by separating coarse grains (minimum size 20 mm in diameter) from water and fine sediment. The measuring station consist 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 (Lenzi et al., 2004). The volume of bedload is measured at 5 min intervals by 24 ultrasonic sensors fitted on a fixed frame over the

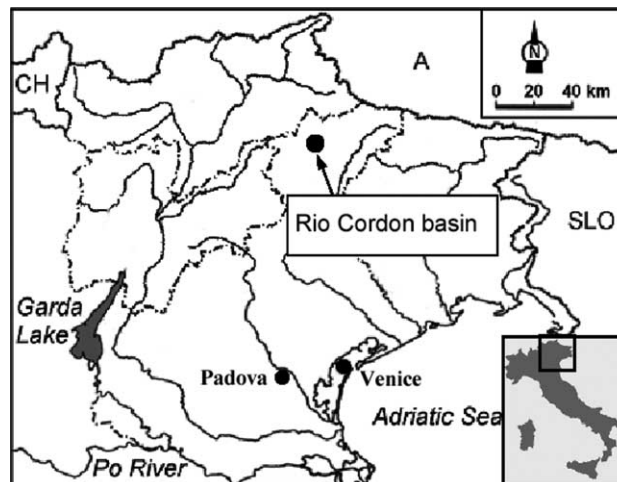


Fig. 1. Location of the study basin.

Table 1
Main characteristics of the Rio Cordon basin and channel

Basin area (km ²)	5.00
Average elevation (m.a.s.l.)	2200
Minimum elevation (m.a.s.l.)	1763
Maximum elevation (m.a.s.l.)	2748
Mean hillslopes gradient (%)	52
Length of the main channel (km)	2.84
Mean width of the main channel (m)	5.7
Mean gradient of the main channel (%)	17
Annual precipitation (mm)	1100
Maximum water discharge measured (m ³ s ⁻¹)	10.4
Mean water discharge measured (m ³ s ⁻¹)	0.26
Minimum water discharge measured (m ³ s ⁻¹)	0.05

storage area (Lenzi et al., 1999). Suspended sediment is measured by two turbidimeters: a Parotech SDM-10 light absorption and a Hach SS6 light-scatter instrument. Flow samples are gathered automatically using a Sigma pumping sampler installed at a fixed position in the inlet channel.

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 total area of 0.262 km² (i.e. 5.2% of basin area). For each area, sketches, photographs and sediment samples were taken. The distribution of their particle-size showed that the material of active sediment sources is widely variable ranging from silt to gravel. Active sediment sources are mainly bare slopes, overgrazed areas, shallow landslides, eroded stream banks and minor debris flow channels (Lenzi et al., 2004).

The Rio Cordon basin climatic conditions are typical of Alpine environments. The main channel is a steep, cobble/boulder-bed stream draining a small high-altitude catchment where snow-related processes (i.e. snowpack accumulation and snowmelt runoff) dominate from November to May. However, the response time of such a small basin is very short, thus significant flooding occurs during intense, short-duration rainfall. Runoff is usually dominated by snowmelt in May and June but summer and early autumn floods also represent an important contribution to the flow regime. Usually late autumn, winter and early spring lack noticeable runoff. Flood duration is accordingly brief, so that the flow is capable of transporting sediment downstream during only a limited period of time, owing to the coarseness of

the streambed material. On average, only one to two events per year are able to cause bedload transport in the Rio Cordon (Lenzi et al., 2004).

The station has been continuously working since 1986, and during the 1986–2003 period the catchment has experienced different kinds of events, such as a low-recurrence flash flood that removed the bed armouring and altered the step pool structure (14th September 1994), as well as several long snowmelt and cyclonic events that scoured pools and removing their finer sediments. Furthermore, there has been unlimited sediment-supply events in concomitance with mud and debris flows on the steep tributaries (Lenzi et al., 2004).

Previous studies in the Rio Cordon have focused on: morphological structures and sedimentology of the streambed (Lenzi, 2001); bedload transport rate (D'Agostino and Lenzi, 1999; Lenzi et al., 1999, 2004); suspended sediment concentration (Lenzi and Marchi, 2000); annual sediment yield (Lenzi et al., 2003), and magnitude–frequency relationships of bedload yield (Lenzi et al., 2004). The travel distance of marked particles has also been studied in the Rio Cordon by Lenzi (2004), using 860 clasts with diameters ranging from 0.032 to 0.512 m surveyed during individual flood events over the periods 1993–1994 and 1996–1998.

3. Methodology

3.1. Bankfull discharge field identification

Bankfull stage conditions were directly observed in the Rio Cordon during three floods: 27th November 2002, 12th June 2004 and 1st November 2004 (Fig. 2). During these events, the measured discharge at the exact moment of inspection was around 2.3 m³ s⁻¹. However, although most reaches clearly appeared to be at bankfull, in others it was less obvious. Actually, in high-gradient, coarse-grained streams like the Rio Cordon, several factors make the determination of bankfull stage more difficult than in gravel- or sand-bed rivers, and the values strongly depend on the used methodology (Radecki-Pawlik, 2002). Firstly, parts of the channel and of the banks are frequently not alluvial, featuring bedrock outcrops and/or large immobile boulders derived from hillslope processes.

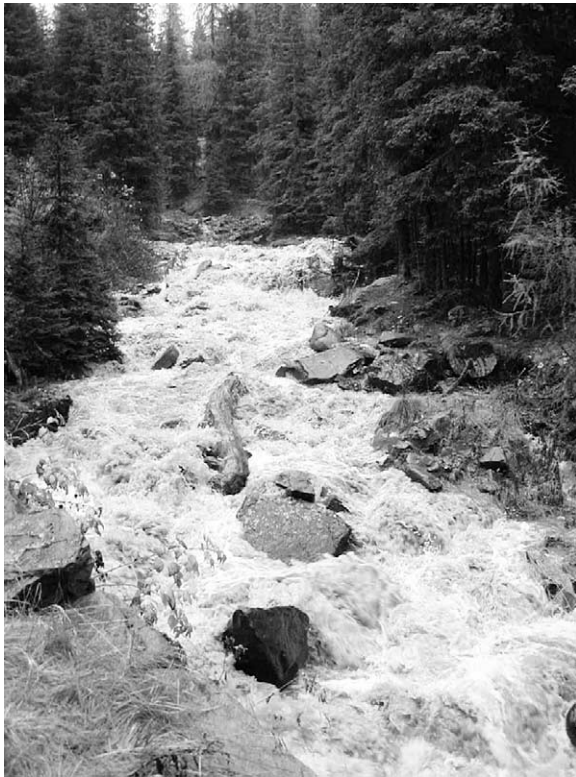


Fig. 2. View of the Rio Cordon main channel at approximately bankfull stage ($2.3 \text{ m}^3 \text{ s}^{-1}$), observed during the 1st November 2004 flood.

Channel adjustment to water and sediment flows are therefore quite limited, becoming more similar to that shown by bedrock channels. Furthermore, vegetation is poorly established on such solid banks, and comprises mostly lichens and mosses, which are not as reliable as grass species in being bankfull markers. Secondly, the adjacent floodplain is often very small or completely absent due to the high confinement of the channels (i.e. high entrenchment ratios). Also, the floodplain may be formed of boulder deposits transported by hyper-concentrated or debris flows, thus presenting a very rough and uneven surface, which is difficult to use as a reference level for the bankfull stage. Finally, low-order, steep streams are usually sediment supply-limited and their relaxation times after channel-changing events can be very high (i.e. decades), compared to lower gradient systems. These factors often mean that high-gradient mountain channels exhibit non-equilibrium characteristics, thus

undermining the conceptual basis for the link between bankfull and dominant discharge. Bearing in mind these uncertainties regarding the determination of bankfull in the Rio Cordon, its stage was recognised considering both the height of the lower limit of the vegetation (Schumm, 1960; Williams, 1978) and the evident changes in sediment size in the small lateral bars (Leopold and Skibitzke, 1967). Other bankfull indicators—minimum width/depth ratio (Wolman, 1955; Pickup and Warner, 1976) and active floodplain elevation (Wolman and Leopold, 1957)—have little significance for the analysed channel type. As reported above, water discharge at bankfull was estimated to be $Q_{\text{br}} = 2.3 \text{ m}^3 \text{ s}^{-1}$ (Mao, 2004), which corresponds to an estimated recurrence interval of 1.6 years by using the lognormal distribution (see Section 3.1). This result is consistent with previous findings regarding bankfull frequency (Dury, 1977; Williams, 1978; Dunne and Leopold, 1978; Leopold, 1994).

3.2. Flow duration curve and recurrence interval of flood peaks

At the Rio Cordon station, water discharge is continuously measured at 5 min intervals during high flows (i.e. when the discharge exceeds a certain threshold), and at hourly intervals during low flows. Giving the short-duration and flashy nature of the floods in the Rio Cordon, daily average discharges—which are often used in the Q_c calculation in gravel-bed rivers—and even hourly average values are not adequate to describe the range and frequency of flows.

In order to build a duration curve based on 5-min intervals, it was assumed that during low flows the discharge remains relatively constant, and the 5-min flow values for these periods were derived from the hourly discharge. By this procedure, the flow duration curve of the 1987–2003 period was calculated from a total of 1788 192 5-min flow values. Owing to the major effects of the 14th September 1994 flood (duration 4 h) on both stream morphology (Lenzi, 2001) and bedload transport (Lenzi et al., 2004), the total flow database was divided in two periods: pre-1994 event (810,552 values) and post-1994 event (977,592 value).

Considering the Rio Cordon hydrological regime, i.e. a typical small Alpine catchment dominated by

snowmelt runoff and by summer and early autumn floods, and the different suspended sediment transport regime of each season, the total database was divided into four periods: spring (snowmelt) from 1st April to 30th June, summer from 1st July to 31st August, autumn from 1st September to 30th November, and finally winter from 1st December to 31st March. The effects of the snowmelt in terms of sediment transport are most evident in May, when generally a long-duration, low-magnitude flood occurs. The lognormal distribution proved to be the best-fitting one in describing both the whole and the grouped (seasonally and pre-/post-1994) discharge data.

In order to evaluate the frequency of occurrence of the floods, the recurrence interval (RI) was estimated from the values of the annual maximum instantaneous water discharge over 17 years, i.e. selecting for each year the largest event in the case of multiple floods per year (Fig. 3). Again, the lognormal distribution was found to provide the best fit (Lenzi et al., 2004).

3.3. Bedload and suspended sediment data

From 1987 to 2003 (17 years) 21 floods involving bedload transport (grain size greater than 20 mm) were recorded at the measuring station (Lenzi et al., 2004). Given the pulsating character of bedload transport and the settling of clasts forming the sediment heap on the storage area of the measuring station, the 5-min interval data of the ultrasonic meters (see Section 2) could seldom be resolved because of a very irregular pattern. Therefore, bedload

volume increments were mostly associated to 1-h time intervals, for a total of 243 h bedload increments. Averaged bedload rates (in Kg s^{-1}) were calculated for each hourly increment. These bedload rates were then coupled to the mean water discharge corresponding to the relative time interval, and the best fit equation is a power relationship (Eq. (1); $R^2=0.78$), where Q_{sb} is the bedload discharge in kilogram per second and Q is the liquid discharge in cubic metre per second.

$$Q_{sb} = 6.45 \times 10^{-3} Q^{5.368} \quad (1)$$

However, since the exceptional 14th September 1994 event showed bedload intensities much higher than all the others floods (up to 200 Kg s^{-1} compared to 30 kg s^{-1} for the second highest event) and because a marked difference between pre- and post-1994 is evident (Lenzi et al., 2004), the following computation of these three groups of data will be considered separately.

Regarding suspended sediment transport, the two turbidimeters installed in the experimental station collect measurements every 5-min during flood times. Because different lithologies are present in the Rio Cordon basin, the turbidity–SSC relationship has been analysed and calibrated in laboratory (Lenzi et al., 2003). Besides rainfall-caused flows, snowmelt runoff may be a source of conspicuous contribution to the annual suspended sediment yield in the Rio Cordon basin. Abundant suspended sediment transport was recorded during rapid snowmelt phases caused by high-temperature and rainfall. In contrast,

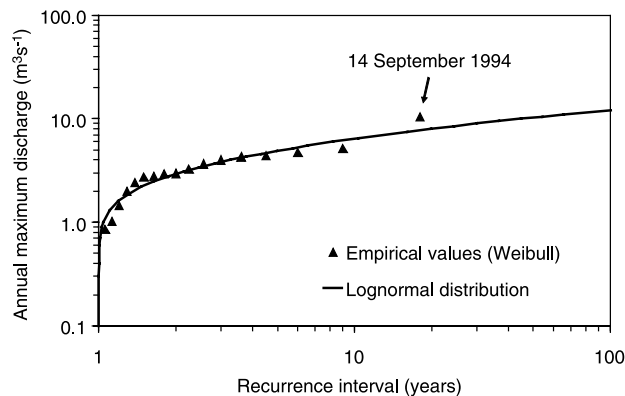


Fig. 3. Recurrence intervals of annual maximum peak discharges.

the combination of early snowfalls, permanent snow cover through the winter, and slow snowmelt with no rain would lead to a scant suspended sediment load (Lenzi et al., 2003). Given the nature of the hydrological regime, the different character of the floods and of the related SSC, the annual cycle has been divided as previously defined (see Section 3.1) in four seasons. From 1987, 1287 SSC has been registered during the snowmelt period; 1010 and 1542 in the summer and autumn time, respectively.

Empirical correlations between water discharge and SSC has been derived for the three seasons showing transport of sediment by suspension. The SSC– Q water discharge rating curve for snowmelt flows is expressed by the following best-fit equation:

$$\text{SSC} = 4.004 + (2.198 \ln Q) \quad (2)$$

where SSC is the suspended sediment concentration expressed in gram per litre and Q is the water discharge in cubic metre per second. Eqs. (3) and (4) were obtained from summer and autumn data, respectively:

$$\text{SSC} = 0.1009Q^{2.447} \quad (3)$$

$$\text{SSC} = 0.1001Q^{2.026} \quad (4)$$

Since winter is characterised by very low flows, the period from December to March was not been taken into consideration for the suspended sediment contribution. No significant distinction in SSC– Q relationship was recognised between pre- and post-1994 periods.

3.4. Effective discharge computation

The Wolman and Miller's (1960) procedure for computing effective discharge, involves the use of the flow frequency distribution and a sediment rating curve. The effective discharge Q_e corresponds to the peak of the curve obtained multiplying the two functions. Hereafter, Wolman and Miller's method will be called the 'traditional' approach, in contrast to the methodology (see Crowder and Knapp, 2005) that uses the actual percentage of occurrence and the average sediment rate measured for each flow class. This latter procedure, since it involves mean transport rates, will be referred to as the 'mean' approach.

In this study, the 5-min interval flow values are considered in the Q_e computation, in contrast to the vast majority of studies, which have commonly used mean daily values (Andrews, 1980; Nolan et al., 1987; Emmett and Wolman, 2001; Vogel et al., 2003). Due to the flashy nature of the flood events in such a small, steep basin, a very short time interval is in fact crucial. The 5-min discharge interval option involves a very wide flow range (from $0.01 \text{ m}^3 \text{ s}^{-1}$ for winter base-flow to $10.4 \text{ m}^3 \text{ s}^{-1}$ for the 14th September 1994 peak flow), which causes some uncertainties about the choice of the number/size of the discharge intervals, one of the most important variables influencing the Q_e computation, as pointed out by Sickingabula (1999); Crowder and Knapp (2005). Biedenharn et al. (1999) proposed an iterative procedure in which size/number of classes are assigned and then slowly reduced until each class contains at least one flow event. Such a method, applicable in lowland rivers (long-duration, slowly-rising floods) with mean daily discharge, proved to be inappropriate in the Rio Cordon. In order to identify how the number of class intervals can influence the determination of Q_e , its computation was carried out with 105, 53, 42 and 21 classes, which flow intervals are 0.1, 0.2, 0.25 and $0.5 \text{ m}^3 \text{ s}^{-1}$, respectively. Each flow class is denominated by its central value.

4. Results

4.1. Effective discharge for bedload transport

The availability of hourly values of bedload transport in the Rio Cordon for a very large range of water discharges, made it possible to use both the 'traditional', bedload rating curve approach, and the measured bedload transport rates for each flow class ('mean' approach). By using the Wolman and Miller (1960) approach, the rating curve (Eq. (1)) for bedload transport (Q_{sb}) and the lognormal frequency distribution describing the 5-min flow data were used. Fig. 4a shows both curves and the function, E_b , resulting by their multiplication (see Section 3.3). The Q_{sb} curve starts at $1.25 \text{ m}^3 \text{ s}^{-1}$, which is the minimum value for the application of the Eq. (1), and the E_b curve shows a clear unimodal behaviour, with a peak, corresponding to the effective discharge

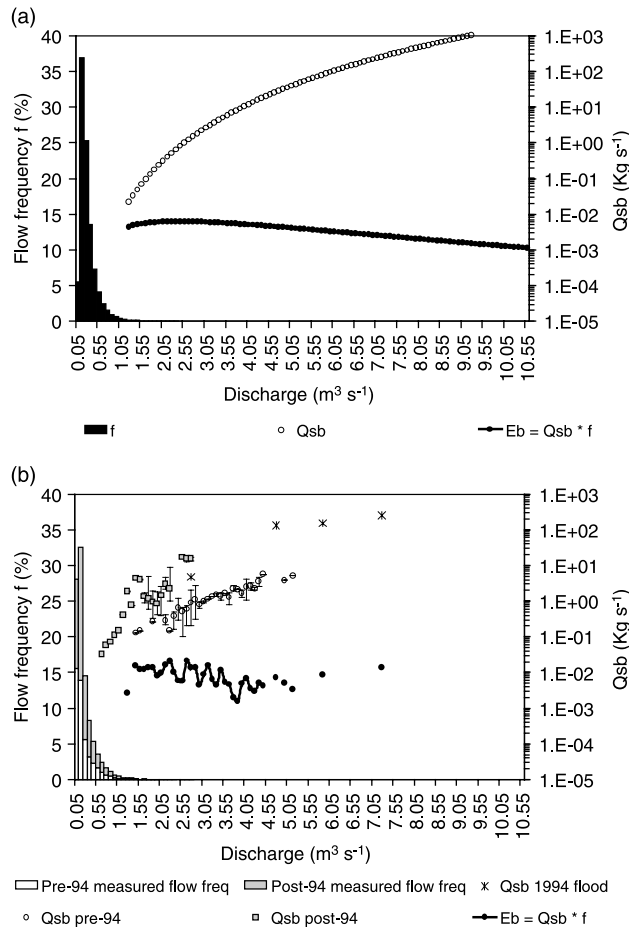


Fig. 4. Effective discharge curves for bedload transport calculated using: (a) 'traditional approach', i.e. bedload rating curve and lognormal flow frequency distribution (Q_{cBRL}); (b) 'mean approach', i.e. measured flow frequencies and mean bedload rates (Q_{cBMM}). The flow class interval is $0.1 m^3 s^{-1}$ (108 flow classes). Bars in Fig. 4b represent the min–max range of bedload rates for each class.

(Q_{cBRL} , i.e. bedload Q_c calculated using the rating curve and the lognormal flow distribution), at $2.45 m^3 s^{-1}$. For higher discharges, the E_b curve decreases due to the progressively lower frequencies of larger flow rates.

The marked differences in bedload transport between the exceptional event of September 1994 and the 'ordinary' floods, and the significantly higher bedload rates featured by the post-1994 with respect to the pre-1994 floods (Lenzi et al., 2004), was accounted for using the 'mean' approach. 5-min flow rates were in fact divided in three periods: pre-1994 flood, post-1994 flood and the 14th September 1994 event, as represented by the histograms in Fig. 3b. The

average bedload transport rate (in kilogram per second) associated with each flow class was then calculated. The pre- and post-1994 measured bedload rates were considered separately, as well as the 1994 flood bedload rates (four values). The E_b curve derives from the multiplication of the measured flow frequencies and the mean bedload rates, weighted according to the belonging of each class to the three different categories (pre-, post- and 1994 flood). This procedure allows us to consider simultaneously the intra- (hysteresis cycle) and the inter-flood (sediment supplies cycles) bedload intensity variation in such a long-term, continuous bedload monitoring. Using this 'mean' approach, the E_b curve turns out to be much

more irregular and to have a very jagged pattern that prevents the identification of a representative peak (Fig. 4b). The actual maximum occurs at $Q_{eBMM} = 2.65 \text{ m}^3 \text{ s}^{-1}$, a values similar to the previously obtained $2.45 \text{ m}^3 \text{ s}^{-1}$ (Fig. 4). Nevertheless, other comparably E_b high values, corresponding to flow rates of 2.25 and $3.15 \text{ m}^3 \text{ s}^{-1}$, are reached, thus questioning the appropriateness and significance of a single Q_e . It is important to bear in mind that Fig. 4 reports the effective discharge analysis conducted using discharges and bedload data grouped in classes with interval of $0.1 \text{ m}^3 \text{ s}^{-1}$.

In order to assess how class size affects the Q_{eB} values, in Fig. 5 the E_b curves obtained either using the ‘traditional’ and the ‘mean’ approach for 0.1, 0.2, 0.25 and $0.5 \text{ m}^3 \text{ s}^{-1}$ flow intervals are reported. It clearly appears that the wider the interval (i.e. the fewer the flow classes) the smoother the curve. The ‘rough’ pattern of the $0.1 \text{ m}^3 \text{ s}^{-1}$ E_b curve is due to the fact that some classes present few bedload data, and some do not even have any. In the latter condition, nil transport rates were assigned to the ‘empty’ flow classes, hence $E_b = 0$. As pointed out by Crowder and Knapp (2005), using the ‘mean’ approach could generate an erratic effective discharge curve.

Considering together the E_b curves computed using the four different flow class intervals (Fig. 6), it appears that the peak values (Q_{eBMM}) becomes smaller and poorly defined as the class size reduces, and, when classes of $0.1 \text{ m}^3 \text{ s}^{-1}$ are considered, the relative importance of the 1994 flood is amplified. In fact, even though the absolute maximum E_b value is reached at $Q_{eBMM} = 2.65 \text{ m}^3 \text{ s}^{-1}$, a secondary high peak is reached by the $7.25 \text{ m}^3 \text{ s}^{-1}$ class, as a consequence of the massive bedload transport rate of 1994 flood (249 Kg s^{-1}).

The influence of flow class interval on the computation of Q_e will be discussed in detail in the Section 5.1.

4.2. Effective discharge for suspended sediment transport

As for bedload transport, effective discharge was computed for suspended sediment transport by the two afore mentioned approaches. No significant differences in SSC were recognised between

pre- and post-1994 periods. However, giving the major distinction in SSC for different seasons, the effective discharge was calculated considering such a seasonal influence. Using the ‘traditional’ approach, Eqs. (2)–(4) were used along with the best-fit, lognormal seasonal flow distribution (see Section 3.3).

Suspended sediment transport intensities (kilogram per second) were obtained by multiplying SSC (in gram per litre) by the mean discharge of each flow class. In order to compute Q_{eS} by the ‘mean’ approach, the mean suspended sediment intensity (Q_{ss}) of each flow class for each season was first calculated. Q_{ss} was then multiplied by the actual seasonal flow frequency of each class. A single E_s curve was finally obtained by adding together the four seasonal values.

Fig. 7 shows the seasonal flow frequencies, the seasonal Q_{ss} and the E_s curves obtained by ‘traditional’ (Fig. 7a) and ‘mean’ (Fig. 7b) approaches applied to data grouped in classes of $0.1 \text{ m}^3 \text{ s}^{-1}$. Likewise in Fig. 4a, the E_s curve in Fig. 7a shows a much smoother trend compared to the ‘mean’ method. Its peak value is reached at $0.55 \text{ m}^3 \text{ s}^{-1}$, whereas the E_s curve reported in Fig. 7b features a jagged trend and peaks at $0.85 \text{ m}^3 \text{ s}^{-1}$. It is evident, nevertheless, that there is a range approximately from 0.45 to $0.85 \text{ m}^3 \text{ s}^{-1}$ with very high E_s values. The E_s curve do not shows high values due to the September 1994 flood data. This is due to the fact that the SSC is measured by turbidimeters—suspension of coarse sand and fine gravel in suspension did not cause comparable increase in turbidity (Lenzi et al., 2003)—and for the manifest higher frequency of flows lower than $1 \text{ m}^3 \text{ s}^{-1}$.

Fig. 8 shows the E_s curve calculated using 0.1, 0.2, 0.25 and $0.5 \text{ m}^3 \text{ s}^{-1}$ as flow intervals and applying both the ‘traditional’ (Q_{eSRL}) and ‘mean’ (Q_{eSMM}) approach. Obviously, it appears that by reducing the number of flow classes (i.e. increasing the flow-step interval), the curve becomes smoother and with a well-defined peak. Given the abundant amount of suspended sediment transport data, even with the smallest interval ($0.1 \text{ m}^3 \text{ s}^{-1}$) there are zero values ($E_s = 0$, i.e. classes with no sediment records) only for the higher discharges ($Q > 4.15 \text{ m}^3 \text{ s}^{-1}$).

Fig. 9 summarizes the results of the ‘mean’ approach with the four analysed flow intervals

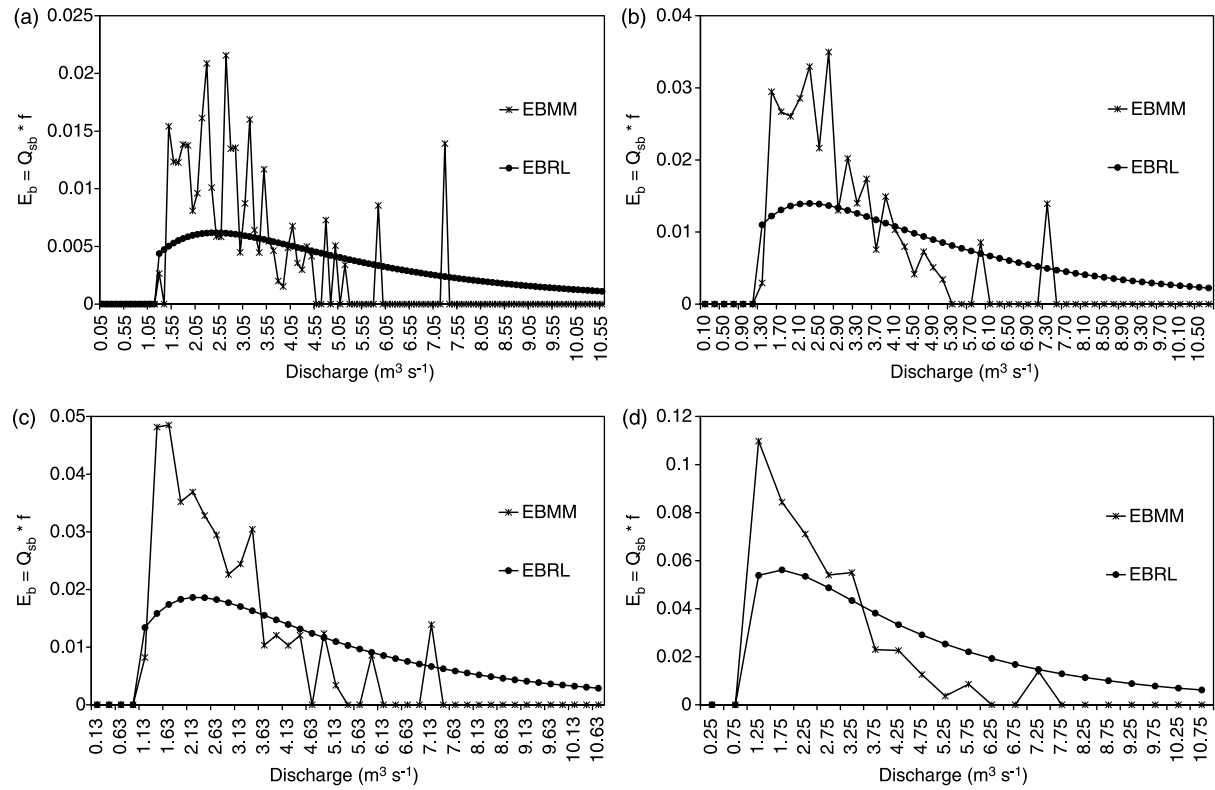


Fig. 5. Effective discharge curves for bedload transport obtained using both the ‘traditional’ and the ‘mean’ approach, with flow class intervals (in cubic metre per second) of 0.1 (a), 0.2 (b), 0.25 (c) and 0.5 (d).

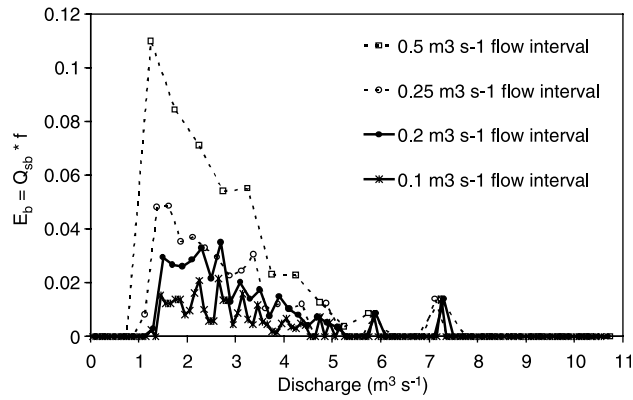


Fig. 6. Comparison of the effective discharge curves for bedload transport obtained using the ‘mean’ approach for the different flow class intervals used in the computation.

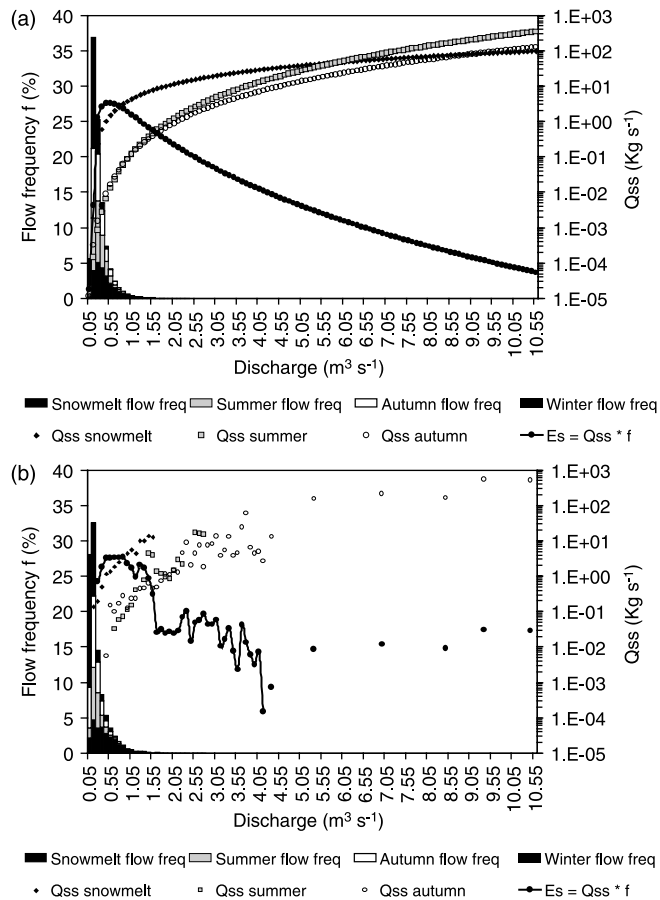


Fig. 7. Effective discharge for suspended sediment transport calculated using: (a) ‘traditional approach’, i.e. suspended sediment rating curve and lognormal flow frequency distribution; (b) ‘mean approach’, i.e. measured flow frequencies and mean suspended sediment rates. The flow class interval is $0.1 \text{ m}^3 \text{ s}^{-1}$ (108 flow classes).

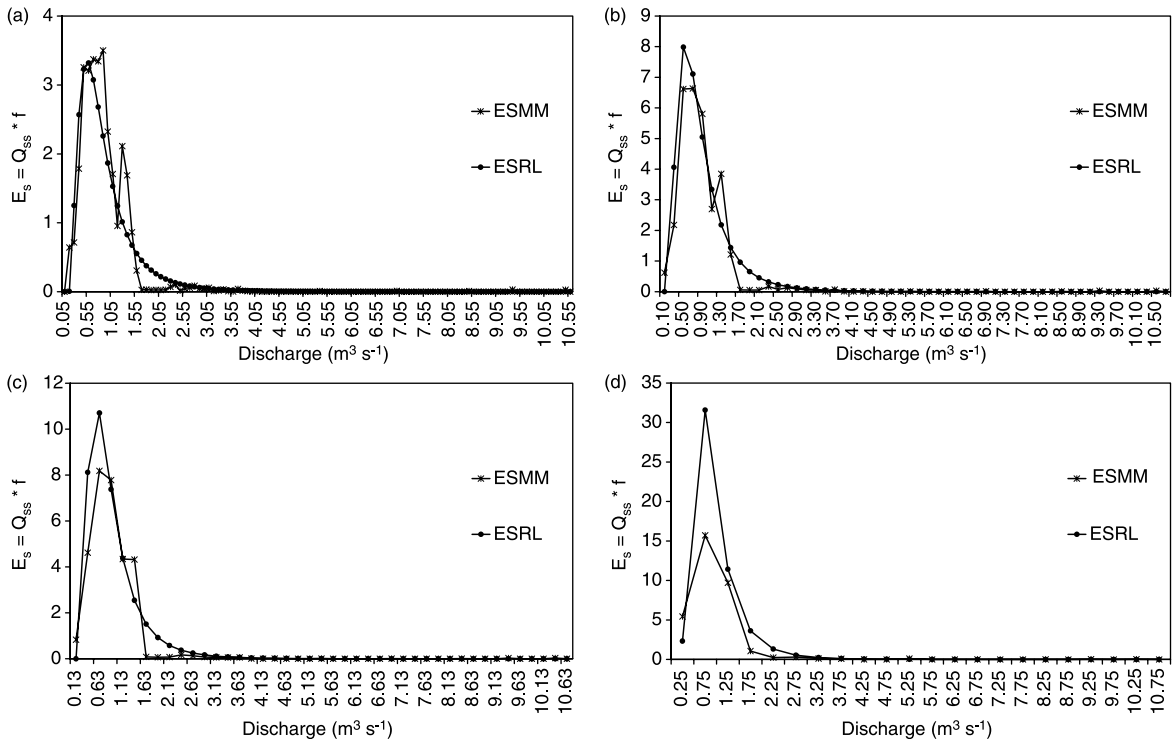


Fig. 8. Effective discharge curves for suspended sediment transport obtained using both the ‘traditional’ and the ‘mean’ approach, with flow class intervals (in cubic metre per second) of 0.1 (a), 0.2 (b), 0.25 (c) and 0.5 (d).

(0.1, 0.2, 0.25 and 0.5 m³ s⁻¹). The somewhat irregular behaviour of the smallest interval (0.1 m³ s⁻¹) curve gradually disappears reducing the class numbers. However, even for this finely

discretized curve, no isolated peaks emerge in correspondence to high flow rates (see for comparison Fig. 6). Higher discharges are therefore are poorly efficient in transporting suspended sediments.

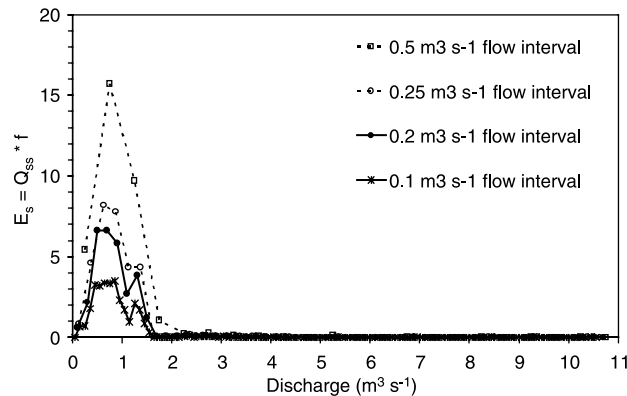


Fig. 9. Comparison of the effective discharge curves for the suspended sediment transport obtained using the ‘mean’ approach for the different flow class intervals used in the computation.

4.3. Effective discharge for total sediment transport

Curves for bedload (E_b) and suspended sediment transport (E_s) were summed in order to obtain the effective discharge for the total sediment transport in the Rio Cordon, considering both the ‘traditional’ and the ‘mean’ calculation approaches (graphs not showed). Due to the major contribution of suspended sediment transport to the total sediment transport in the Rio Cordon (Lenzi et al., 2003), the peaks of the derived E_t curves completely correspond to those for the suspended sediment. Furthermore, the shape of the E_t curves largely follows that of the E_s curve, with the bedload influence starting only for discharge higher than the minimum one for bedload transport ($1.25 \text{ m}^3 \text{ s}^{-1}$).

5. Discussion

5.1. Influence of flow class interval

As pointed out in previous works (Sichingabula, 1999; Biedenharn et al., 1999; Goodwin, 2004; Crowder and Knapp, 2005), there is still subjectivity about the procedure for the Q_e determination. One of the major problems occurs in selecting the number of flow classes (Sichingabula, 1999). In the literature,

different values have been used, but there still lacks a clear-cut criteria for the flow class number selection. This aspect proves to be especially critical in small basins, in which the flow regime is often variable and characterized by flashy, short-duration floods. In these channels the entrainment threshold for bedload transport is usually very high and hard to predict. Also the minimum length of historical data series capable of producing consistent results is still undefined (Biedenharn et al., 1999; Crowder and Knapp, 2005).

Results obtained from the Rio Cordon bedload effective discharge calculation using both ‘traditional’ (Q_{eBRL}) and ‘mean’ (Q_{eBMM}) approaches are summarized in Fig. 10a. The effective discharge values of each of the four selected flow-class intervals are graphed as icons linked by lines. For the ‘traditional’ approach, each Q_e value is associated to an interval box representing the width of the flow class, i.e. a sort of ‘uncertainty’ range increasing with larger classes. In the ‘mean’ approach, added on this imprecision due to the discretization, there is the effect of the irregular pattern of the E_b curves, which renders a Q_{eB} range more significant than a single value (see Section 4.1). Obviously, using the ‘traditional’ approach, the larger the flow class the larger the box, i.e. the lower the precision. Conversely, using the ‘mean’ approach, the irregular behaviour of the E_b curve strongly influences

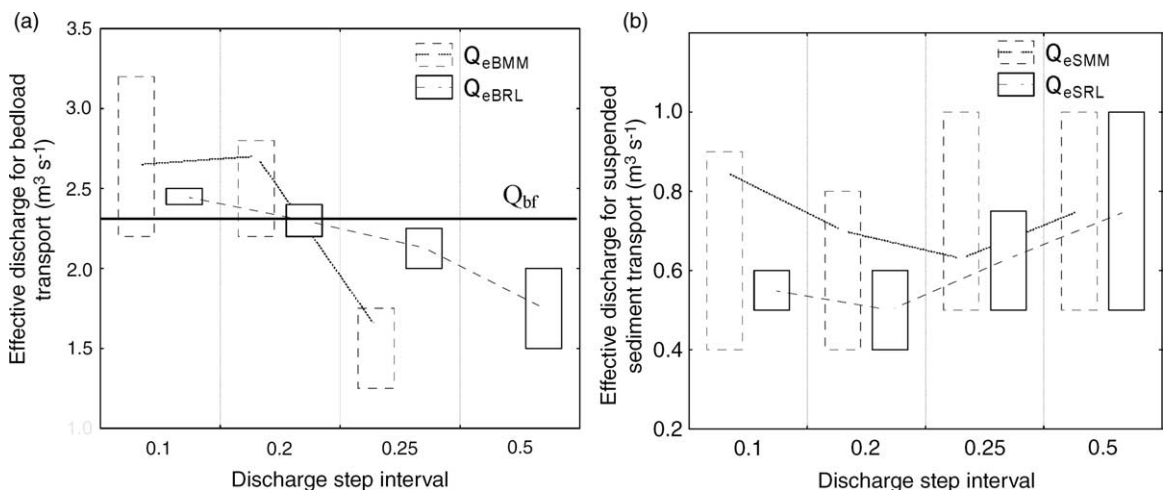


Fig. 10. Effective discharge for bedload (a) and suspended sediment transport (b) calculated using both ‘traditional’ and ‘mean’ approach. Boxes represent the discharge ranges of the effective discharges. The Q_{bf} line visualizes the bankfull discharge ($2.3 \text{ m}^3 \text{ s}^{-1}$).

the discharge range. The Q_{cBMM} value calculated using $0.5 \text{ m}^3 \text{ s}^{-1}$ as the flow interval is not reported, it being considered unreliable because the E_{b} peak is reached at the first flow class (Fig. 5a). A similar situation has also been described by Crowder and Knapp (2005), who recommended increasing the number of class intervals if the peak occurs in the first class.

Considering together the Q_{cB} values, it appears that those calculated by the ‘traditional’ approach (Q_{cBRL}) progressively decrease as the class interval increases (Fig. 10a), ranging from 2.45 to $1.75 \text{ m}^3 \text{ s}^{-1}$, using 0.1 – $0.5 \text{ m}^3 \text{ s}^{-1}$ as flow intervals, respectively. Instead, such a trend is not directly recognizable for the Q_{cBMM} values, which ranges from 3.20 to $1.63 \text{ m}^3 \text{ s}^{-1}$, but the value referring to the $0.5 \text{ m}^3 \text{ s}^{-1}$ is lacking (see above).

Fig. 10b shows the effective discharge for suspended sediment transport (Q_{cS}), again calculated by both the ‘traditional’ and ‘mean’ approaches, similarly to Fig. 10a for bedload transport. A positive relationship between flow interval and Q_{cSRL} is apparent, in contrast to what observed for bedload (Fig. 10a). Using the ‘traditional’ approach, the Q_{cS} values range from 0.5 to $0.75 \text{ m}^3 \text{ s}^{-1}$, and by the ‘mean’ approach from 0.63 to $0.85 \text{ m}^3 \text{ s}^{-1}$.

Therefore, for both bedload and suspended sediment transport, the effective discharge value diverges significantly depending on the computational approach and the number of flow classes (Fig. 10). Using the ‘mean’ approach, which is reckoned the more rigorous and sensible to represent Rio Cordon

data at best, the lower the number of flow classes, the clearer the effective discharge value. Nevertheless, it is important to highlight that when large intervals are selected, the peak class represents a wide range of flows. On the other hand, with $0.1 \text{ m}^3 \text{ s}^{-1}$ as the flow interval, the E curve is so irregular that the effective discharge should be regarded to as a flow range rather than a single value. In conclusion, the effective discharge for bedload and suspended sediment transport can be quantified as 2.25 – 3.15 and 0.45 – $0.85 \text{ m}^3 \text{ s}^{-1}$, respectively.

5.2. Frequency and duration of bankfull, effective and sediment-entraining discharges

Curves showing the cumulative sediment transport as a function of cumulative discharge are reported in Fig. 11. Both bedload and suspended sediment transport are plotted. In the literature, there are some studies reporting about the cumulative percentage of sediment transported by a certain cumulative percentage of discharge. Regarding suspended sediment transport, Webb and Walling (1982) found that 50% of the suspended load was moved by 9% of the total discharge. In Rio Cordon, 50 and 90% of the cumulative suspended sediment transport are moved, respectively, by 95 and 99.5% of the cumulative water discharge (Fig. 11). The upper 50% of suspended sediments is transported by flows which duration is <14 days/year (RI=0.84 year), whereas the upper 10% by flows lasting <1.9 days/year

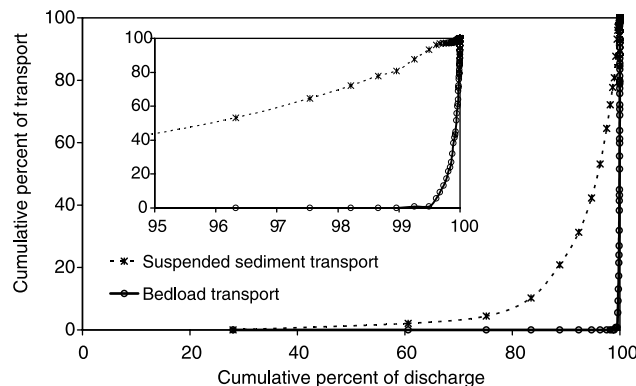


Fig. 11. Relationships between the cumulative water and sediment discharges for bedload and suspended sediment transport. The inner graph shows a closer view of the highest cumulative water discharge.

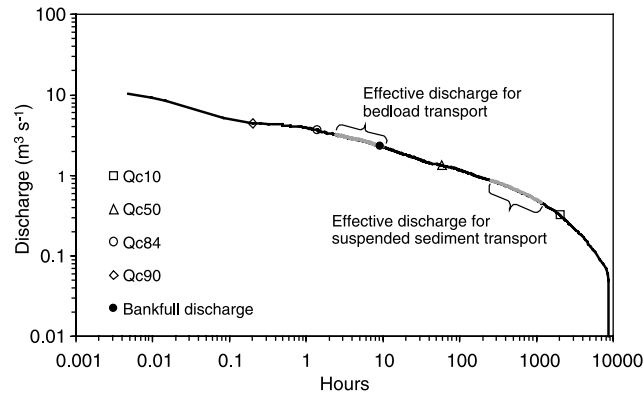


Fig. 12. Flow duration curve based on 5-min flow data. The thicker portions of the curve symbolize the effective discharge range for bedload and suspended sediment transport. The bankfull discharge and the critical discharges for the entrainment of some grain-size percentiles of the streambed are also shown.

frequency flow (RI=1.08 year). The results clearly show that for steep, coarse mountain rivers, relatively higher discharges convey a certain amount of suspended sediment load.

Fig. 12 shows the flow duration curve, in which each discharge is associated to the percentage of time exceedance (h/year). The discharge range most efficient in suspended sediment transport ($0.45\text{--}0.85\text{ m}^3\text{ s}^{-1}$, see Section 4.2) features a recurrence interval of 0.74–0.87 year and a duration of 48.7–11 days/year (Fig. 12). The relative duration thus ranges between 11.2 and 2.5%, confirming previous results reported by Wolman and Miller (1960); Sickingabula (1999), among others. However, contrary to these works, here the effective discharge for suspended sediment is not considered as a channel-forming flow.

Considering now the bedload transport, it is evident that the importance of high flow rates is much more marked, and a ‘zoom’ is needed to visualize its plot (Fig. 11). The majority (>50%) of sediments trapped in the storage area is in fact transported by very infrequent flows (99.9% of the cumulative discharge) that occur <0.22 days/year only (i.e. 5.3 h/year; RI=1.87 year). If expressed in terms of the bankfull discharge ($Q_{\text{bf}}=2.3\text{ m}^3\text{ s}^{-1}$), it turns out that flows up to the bankfull stage transport the 97.7% of the sediment in suspension, but only the 38.3% of the bedload (Figs. 11 and 12). The

recurrence interval of the bankfull discharge approximates 1.6 year, and is exceeded 9.15 h/year (0.025% of the time). Looking at the effective discharge range for bedload transport ($2.25\text{--}3.15\text{ m}^3\text{ s}^{-1}$, see Section 4.1), its duration is between 10 and 2.5 h/year (0.104 and 0.028% of the time), with a recurrence interval of 1.58–2.31 years (Fig. 12).

Lenzi et al. (in press) quantified the threshold of incipient motion for each particle size of the Rio Cordon bed alluvium, analysing both the travel distances of marked particles and the flow competence (i.e. the largest grain size transported to the station by each flood event). In Fig. 12, Q_{cS} and Q_{cB} are shown and compared to the critical discharge for the entrainment of some significant grain size percentiles. It emerges that the Q_{c10} (critical discharge for the entrainment of $D_{10}=26\text{ mm}$) is lower than Q_{cS} . Such a critical discharge ($0.32\text{ m}^3\text{ s}^{-1}$) has a recurrence interval of 0.7 years and a duration of 85.3 days/year, whereas the Q_{c50} ($D_{50}=119\text{ mm}$) was established (Lenzi et al., in press) to be $1.33\text{ m}^3\text{ s}^{-1}$ (RI=1.07 years), which is exceeded only 2.4 days/year on average. The entrainment discharge for D_{84} (357 mm) and D_{90} (451 mm) results to be more infrequent than the effective discharge for bedload transport. Q_{c84} and Q_{c90} were in fact quantified as $3.67\text{ m}^3\text{ s}^{-1}$ (RI=2.87 years) and $4.55\text{ m}^3\text{ s}^{-1}$ (RI=4.17 years), with a duration of 1.4 and 0.2 h/year, respectively (Fig. 12).

5.3. The geomorphic significance of the effective discharge and high-magnitude, low-frequency floods

As pointed out by Crowder and Knapp (2005) and earlier by Nash (1994); Knighton (1998), the Q_e evaluation is significantly influenced by the sediment fraction used in its computation. In the Rio Cordon, the effective discharge for suspended sediment transport is significantly smaller than the field-identified bankfull discharge (0.45–0.85 vs $2.3 \text{ m}^3 \text{ s}^{-1}$). This suggests that suspended sediment transport plays a minor geomorphic role in steep, coarse channels, even though suspended sediment is quantitatively important in the long-term sediment yield (Lenzi et al., 2003).

The effective discharge for bedload transport is substantially higher ($2.25\text{--}3.15 \text{ m}^3 \text{ s}^{-1}$) than the one for the suspended load, and approximately similar to the bankfull discharge ($2.3 \text{ m}^3 \text{ s}^{-1}$), thus the bedload transport could be regarded as the main geomorphologic agent (as previously pointed out by Leopold, 1992; Nash, 1994; Andrews and Nankervis, 1995; Emmett and Wolman, 2001). However, the effective discharge of bedload transport may not generally be linked to the bankfull stage in such high-gradient, coarse-grained streams, as originally envisaged for low-gradient, sand-bed rivers at the long-term equilibrium (Wolman and Miller, 1960; Leopold et al., 1964; Andrews, 1980; Leopold, 1994; Rosgen, 1996). Emmett and Wolman (2001), in fact, argued that as particle size and flow variability increase, the channel size and form could be related to the critical threshold of transport rather than to the quantity of sediment transported.

Furthermore, it is important to stress that the Rio Cordon bankfull discharge was identified in the field by noting the evident changes in sediment size and vegetation in small lateral bars (Leopold and Skibitzke, 1967; Williams, 1978), rather than using the minimum width/depth ratio and the active floodplain elevation (Wolman, 1955). Such a bankfull stage may have a lesser geomorphologic significance than that detectable in lower-gradient rivers.

Looking at the Q_{eB} curve for $0.1 \text{ m}^3 \text{ s}^{-1}$ as flow interval (Fig. 5a), it appears that beyond the effective discharge range ($2.25\text{--}3.15 \text{ m}^3 \text{ s}^{-1}$) there are additional peaks (5.85 and $7.25 \text{ m}^3 \text{ s}^{-1}$) which correspond to the bedload transport during the 14th

September 1994 flood. This suggests a relatively high effectiveness of the 1994 exceptional flood (RI=53 years; Lenzi et al., 2004). Lenzi (2001) reported on the morphological evolution of step-pool morphology after this flood. The channel was filled by the large volume of sediments, and an increase (25–30%) in step wavelength was observed along with a general channel widening. During the subsequent years, the ordinary flood events progressively scoured out sediments from pools and caused a better definition of step-pool profile (Lenzi, 2001).

Therefore, it is possible to compare the impacts of low-frequency, high-magnitude floods vs the more frequent effective discharge for bedload transport, picturing two dominant discharge ranges having distinct geomorphological roles in the Rio Cordon. The two ranges are:

- (a) A relatively frequent (RI ~ 1.5–3 years) flow range, related to the bedload effective discharge, responsible for channel form maintenance. Main effects attributed to this range are linked to bed-form shaping such as formation and alteration of minor steps, pools scouring, increase of the step-pool steepness factor, and sediment redistribution by selective grain entrainment;
- (b) More infrequent (RI ~ 30–50 years) flows (on the order of the 14th September 1994 flood) responsible for macro-scale channel changes, such as channel width adjustment, formation and alteration of major steps and plan-form changes. Eventually, events with larger recurrence interval will most likely occur as debris flows, bringing about catastrophic perturbations to the system. In fact, the peak of the September 1994 flood featured near hyper-concentrated characteristics. More uncertain is the lower limit of this flow range, due to the lack of events with recurrence interval between 10 and 50 years.

Along with the widely accepted concept of effective discharge expressed by Wolman and Miller (1960) for lowland sand-bedded rivers in temperate-humid environments with prevalent fine suspended sediment transport, the importance of the low-recurrence high-magnitude events as flow ranges having significant geomorphic influences is thus evident for steep, high-altitude channels. In fact,

the behaviour of the Rio Cordon stream seem to be more linkable to what is shown by non-alluvial systems or streams in semiarid and tropical-humid regions (Pickup, 1991; van Niekerk et al., 1995), in which only high-magnitude events are capable to affecting morphological channel changes (Kochel, 1988). When the systems are characterized by highly variable regimes, the river form requires adjustments to multi-scale discharges (Dollar, 2002), and the morphology often results in nested channel architectures.

The magnitude–frequency of large floods, compared to more frequent events, has been difficultly related to their geomorphic impacts, mainly due to the limited length of streamflow records and to the scarce availability of long series of sediment transport data (Andrews, 1980). However, the critical geomorphological role of high-magnitude floods had been previously reported by Baker (1977); Newson (1980); Baker and Pickup (1987); Osterkamp and Costa (1987), and Vogel et al. (2003). Investigating the 2001 flood impacts on the Hungry Mother River (Virginia), Phillips (2002) put forward the notion of a bimodal dominant discharge pattern, describing the channel maintaining role of near bankfull flows and the effects of the rare floods (recurrence intervals measured in decades) on the transport of the coarser bed material and on channel banks erosion.

6. Conclusions

Effective discharge is defined as the flow rate that is most effective in the long-term transport of sediment. In this paper the effective discharge was calculated using both the ‘traditional’ (best-fit flow frequency distribution and a sediment rating curve) and the ‘mean’ approach. The latter involves the real frequency of occurrence and the average measured sediment rates for each flow class. With the ‘traditional’ approach, the choice of flow class size/number exerts a strong influence on the effective discharge value. By the ‘mean’ approach, the effective curve features an irregular pattern, which tends to become smoother when the number of flow classes diminishes. However, the complex pattern deriving from the use of measured data questions the appropriateness of a single value for the effective

discharge, both for suspended and bedload transport. Given that the effective discharge for suspended sediment transport was quantified as 20–36% of the bankfull discharge in the Rio Cordon, it seems reasonable to argue that it does not play a significant role in channel-forming processes. On the contrary, the bedload effective discharge was found to be slightly higher, yet comparable, to the bankfull discharge. Therefore, bedload transport proves to be more appropriate to describe and analyse channel formation-maintenance processes in steep mountain rivers.

The effective discharge curve for bedload transport obtained by the ‘mean’ approach (Q_{cBMM}), shows a marked jagged pattern and a single peak is thus thought to be poorly representative. The non-unimodal behaviour of this curve is due to various factors that characterize the dynamics of water and sediments in steep mountain streams (i.e. the ‘flashy’ flow regime and the high motion thresholds for bedload transport). The bedload effective discharge curve also shows a secondary peak in correspondence to high flow rates associated to the September 1994 exceptional flood (RI=53 years). Therefore, this research suggests that two discharge ranges may exert geomorphological impacts on mountain rivers: (a) relatively frequent floods (RI~1.5–3 years) responsible for maintaining the channel form in terms of pool depth, and step-pool steepness; and (b) more infrequent, higher flows (RI~30–50 years) responsible for macro-scale channel shaping in terms of major step destruction–creation, channel width adjustments and plan-form changes.

The Rio Cordon seems to reflect general behaviour reported by Nash (1994) and Dollar (2002), who underlined that when fluvial systems are characterized by highly variable regimes, the river form requires adjustments to multi-scale discharges and the morphology often result in nested channel architectures.

Hitherto, almost all the studies on effective discharge have been conducted considering suspended sediment transport in sand- or gravel-bed rivers and using average daily flow data. Further investigations are thus required on small headwater streams, where long-term sediment monitoring programs are needed in order to clarify the geomorphic effectiveness of near-bankfull flows and of high-magnitude, low-frequency flood events. Finally,

the influence of flow class size, methodological approach and sediment fraction involved in the calculation of the effective discharge, deserves further attention in order to minimize the subjectivity that still remains in the computational procedure.

Acknowledgements

The Avalanche Center of Arabba (Veneto Region), in particular Dr G.R. Scussel and Mr W. Testor, are kindly acknowledged for their assistance and for providing data from the Rio Cordon. Funding for this research was provided by the ‘Epic Force’ Project EC Contract Number INCO-CT-2004-510735, from the MIUR project PRIN 2004 Number 2004072251 ‘Opere di riqualificazione ambientale dei corsi d’acqua: dalla scala di laboratorio a quella di campo’, and from the University of Padova Project ‘Valutazione della pericolosità connessa a colate detritiche su conoidi alpini’. Ms Julie Cottis is acknowledged for revising the English text.

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