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Bankfull and bed load effective discharge in a steep boulder-bed channel

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Abstract In order to achieve a better understanding of the physical processes involved in incipient bed load transport and channel-forming conditions in high-gradient streams, bed load rate and flow discharge data provided by the Rio Cordon measuring station were analysed. From 1987 to 2003, 22 floods characterized by bed load transport were recorded at the measuring station. From field surveys, the bankfull discharge was estimated to be 2.3 $m^3 s^{-1}$, with a return period of 1.6 years (lognormal distribution). This is consistent with previous findings regarding the frequency of bankfull conditions. Based on the flow duration curve, bankfull stage is exceeded nine hours per year. The effective discharge for bed load transport, i.e. the flow transporting the greatest amount of bed load over a long period, was estimated to be 2.45–2.65 $m^3 s^{-1}$, which is close to the estimated bankfull discharge. Uncertainties associated with establishing the effective discharge are identified and discussed.

Key words Alps; bankfull discharge; bed load transport; duration curve; effective discharge; experimental basin; high-gradient streams

INTRODUCTION

Alluvial rivers adjust their channel dimensions to the range of flows that are capable of mobilizing their sediment boundaries. Since the early work by Schaffernak (1922), many authors have proposed that a single representative discharge may be used to define the stable channel geometry in the long term. This representative "dominant" (i.e. channel-forming) discharge has been associated with different concepts by different researchers, including the field-identified bankfull discharge (Wolman & Leopold, 1957), a specified recurrence interval discharge (Dury *et al.*, 1963; Williams, 1978) and the effective discharge for sediment transport (Wolman & Miller, 1960; Andrews, 1980). Such a variety of approaches has led to some confusion about both terminology and understanding of the fundamental processes involved.

Bankfull discharge is the maximum discharge that a channel can convey without overflowing onto its flood plain, and is considered to have morphological significance because it represents the breakpoint between channel and flood plain processes. It is commonly determined by identifying the bankfull stage and then determining the associated discharge. Among the most common indicators of bankfull stage is the elevation of the active flood plain (Wolman & Leopold, 1957), the maximum elevation of channel bars (Wolman & 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 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 & Warner, 1976). However, none of these field methods can be used in isolation to obtain reliable results (Williams, 1978).

Due to the difficulties associated with identifying bankfull discharge from field evidence, many researchers have related the channel-forming discharge to a specific recurrence interval discharge, analysing at-equilibrium natural channels where bankfull stage could be easily determined and stream gauges were located in the vicinity. Under these conditions, bankfull discharge 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 of bankfull discharge often approximates the 1.5-year flow event (Dury *et al.*, 1963; Williams, 1978; Leopold, 1994), although substantial variations around this average value have been noted (Pickup & Warner, 1976; Nash, 1994). Williams (1978) showed that in 35 rivers in the USA the recurrence interval associated with the bankfull discharge varied between 1 and 32 years, and that only about a third of the rivers had a bankfull recurrence interval between one and five years.

Finally, the effective discharge is defined as the flow rate that is most effective in the long-term transport of sediment (Wolman & Miller, 1960), and thus as the increment of discharge that transports the greatest proportion of the annual sediment load over a period of many years (Andrews, 1980). The effective discharge incorporates the principle put forward by Wolman & Miller (1960) that the channel-forming discharge is a function of both the magnitude of sediment-transporting events and their frequency of occurrence. It is calculated by multiplying the flow frequency curve and the sediment transport rating curve. The peak of this derived distribution represents the effective discharge.

The present paper analyses the applicability of the three approaches described above in steep mountain streams, by comparing their results for an instrumented catchment, the Rio Cordon, located in the eastern Italian Alps.

CATCHMENT AND CHANNEL DESCRIPTION

The research was conducted in the Rio Cordon catchment (5 km^2), a small stream in the Dolomites, located in the eastern Italian Alps. The solid geology consists of dolomite, which provides the highest relief in the catchment, volcaniclastic 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 by the following percentiles (in mm): $D_{16} = 20$, $D_{50} = 90$, $D_{84} = 260$, $D_{90} = 330$ (Lenzi *et al.*, 1999). 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.

The instrumentation for monitoring water discharge, suspended sediment and bed load transport at the Rio Cordon experimental station have been described in detail in previous papers (Lenzi *et al.*, 1999, 2004). 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).

FLOOD FREQUENCY AND FLOW DURATION ANALYSIS

From 1987 to 2003 (17 years) 21 floods involving bed load transport (grain size greater than 20 mm) have been recorded at the measuring station (Lenzi *et al.*, 2004). Given the pulsating character of bed load transport and the settling of clasts forming the sediment layer, only the hourly bed load increment has been used, rather than the 5-min interval data originally recorded.

In order to evaluate the frequency of occurrence of the flood events, the recurrence interval (RI) was estimated from values of annual maximum instantaneous water discharge over 17 years (Fig. 1), i.e. selecting for each year the largest event in the case of multiple floods per year. The lognormal distribution was found to provide the best fit.

Water discharge is continuously measured at 5-min intervals during floods (i.e. when the discharge increase exceeds a certain threshold), and at hourly intervals during ordinary flows. In order to build a duration curve based on the finer resolution of 5 min, it was assumed that during ordinary flows the discharge remains relatively constant within an hour, so that the same hourly value was associated with the corresponding 5-min discharges during non-flood periods. By this procedure, the flow duration curve was calculated from a 5-min data values total of 1 788 192.

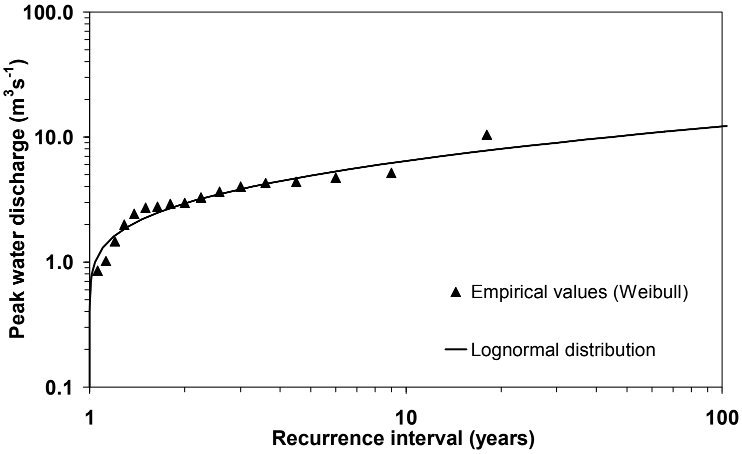

Fig. 1 Magnitude–frequency relationship for annual maximum peak discharge. Empirical values calculated by Weibull's plotting position ($i/N + 1$) are plotted with the curves of the lognormal distributions.

DETERMINATION OF BANKFULL AND EFFECTIVE DISCHARGE

Bankfull discharge

Bankfull stage, i.e. water depth approximately equal to channel depth (see Introduction), was observed in the Rio Cordon on two occasions: on 27 November 2002 and on 12 June 2004 (Fig. 2). During both events, the discharge measured at the station at the exact

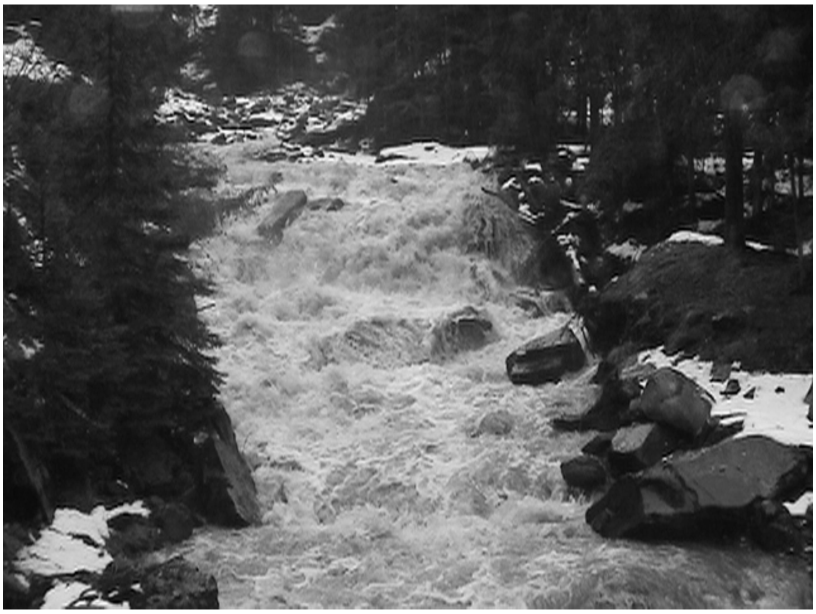

Fig. 2 Rio Cordon at the estimated bankfull discharge of 2.3 m^3 s^{-1}, observed during the November 2002 flood.

moment of observation was 2.3 m^3 s^{-1}. However, although some reaches clearly appeared to be at bankfull, this was less obvious for others: with the flow in some being below the bank line, whilst in others the flow was slightly overflowing the channel. In fact, in high-gradient, cobble/boulder-bed streams like the Rio Cordon, several factors make the determination of bankfull stage more difficult than in gravel- or sand-bed rivers. First, parts of the channel and of the banks are frequently not alluvial, featuring bedrock outcrops and/or large immobile boulders derived from hillslope processes. Channel adjustment to water-sediment flows is therefore heavily reduced, becoming more similar to that shown by bedrock channels. Furthermore, vegetation is poorly established on such solid banks, and most is lichens and mosses, which are not as reliable as grass species as bankfull markers. Secondly, the adjacent flood plain is often very small or completely absent due to the high confinement of the channels (i.e. high entrenchment ratios). Also, the flood plain can be mainly composed 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 bankfull stage. Finally, low-order, steep streams are usually sediment supply-limited and relaxation times after channel-changing events can be very high (i.e. decades), compared to lower gradient system. 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, 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 discussed in the last section. This result is consistent with previous findings regarding bankfull frequency (see Introduction). By using the flow duration curve presented in the last section, flow rates equal or exceeding bankfull stage occurred on average for 9 h year^{-1} (0.025% of the time).

Effective discharge

In contrast to the vast majority of studies on effective discharge, the bed load transport rate is considered here due to its ultimate importance for channel morphology in mountain streams. In fact suspended sediment, even though important for the long-term sediment yield (Lenzi *et al.*, 2003) provides only a minor contribution to changes in channel morphology in such high-energy systems. The availability of hourly values of bed load transport in the Rio Cordon for a very large range of water discharges (for their derivation and analysis, see Lenzi *et al.*, 2004), 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.

The results provided by the traditional Wolman & Miller (1960) approach, involving the use of a sediment rating curve and a flow frequency curve, can be considered first. In our case, the former is the bed load rating curve:

$$Q_s = 6.45 \times 10^{-3} \times Q^{5.37} \qquad (r^2 = 0.783, p = 0.05) \qquad (1)$$

where Q_s is the bed load transport rate in kg s^{-1} and Q is the water discharge in m^3 s^{-1}.

For the flow frequency curve f, the lognormal distribution was found to provide the best fit to the Rio Cordon empirical 5-min data. The product of the two curves $E = f \times Q_s$ (Fig. 3, log-scale) starts at 1.4 m^3 s^{-1}, which is the minimum value for the application of equation (1), and reaches its peak at a water discharge of 2.45 m^3 s^{-1}. Above this discharge value, it decreases due to the progressively lower frequencies of larger flow rates. The value 2.45 m^3 s^{-1} (RI = 1.72 years, was equalled or exceeded on average 7 h year^{-1} or 0.020% of the time), therefore represents the effective discharge, and is very close to the estimated bankfull discharge of 2.3 m^3 s^{-1}.

Figure 4 shows the same analysis, but using instead the measured bed load transport rates and the empirical flow frequencies, grouped in classes of 0.1 m^3 s^{-1}. Due to the abundance of measured bed load data for discharges lower than about 5 m^3 s^{-1}, the average bed load transport rate associated with each flow class was calculated. For

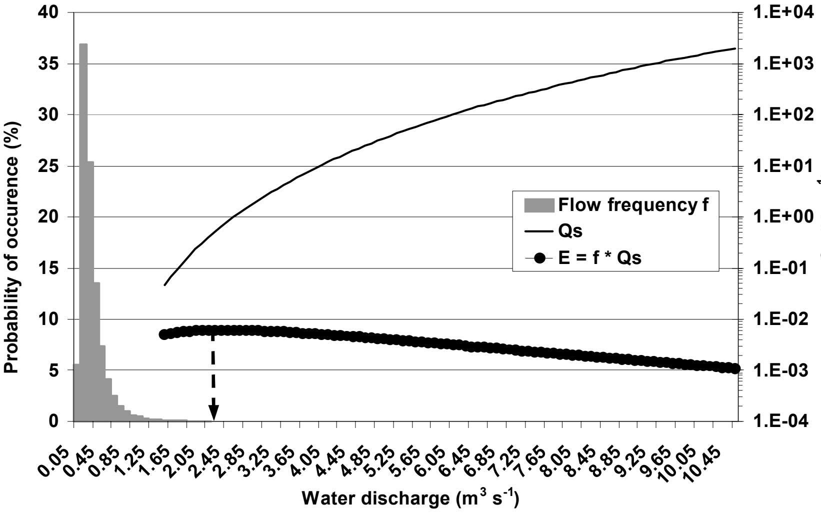

Fig. 3 Effective discharge calculated using the bed load rating curve. The peak of the E (arrow) curve identifies the effective discharge at $Q = 2.45$ m^3 s^{-1}.

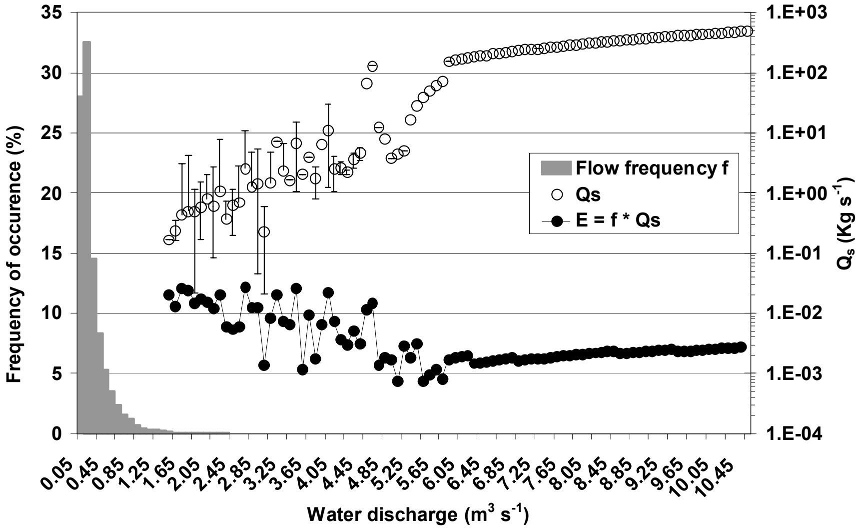

Fig. 4 Effective discharge calculated using the actual bed load rates (Q_s: circles represent average values and bars the min-max range per each class).

higher discharges, achieved only during a single flash-flood event (September 1994, peak Q = 10.4 m^3 s^{-1}, RI = 53 years, see Lenzi *et al.*, 2004), the availability of only three measured bed load rates has meant that interpolated values based on these data have been assigned to flow classes lacking bed load transport rates. Using this approach, the E 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 m^3 s^{-1}, similar to the previously obtained 2.45 m^3 s^{-1} (Fig. 3). Nevertheless, three other high values, very close to the absolute maximum, are reached at 1.65, 3.45 and 3.95 m^3 s^{-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 (graphs not shown).

CONCLUSIONS

In the Rio Cordon, a steep boulder-bed channel in the Italian Alps, the bankfull discharge was estimated from field observations to be 2.3 m^3 s^{-1}. Applying an annual maximum flood frequency analysis over 17 years, such a flow rate can be estimated to recur every 1.6 years (lognormal distribution), in accordance with previous findings about frequency of bankfull conditions. Considering the duration curve, bankfull stage is equalled or surpassed for nine hours per year. The effective discharge for bed load transport, i.e. the flow transporting the greatest amount of bed load in the long term, is very similar (2.45 m^3 s^{-1}) to the bankfull value, if calculated using the bed load rating curve-fitted flow frequency distribution approach. Using empirical values for both flow frequencies and bed load transport rates, provides an effective discharge of 2.65 m^3 s^{-1}, although a very complex pattern is evident in this case that questions the appropriateness of a unique value of effective discharge. Given the large uncertainties and subjectivity still existing in the determination of the effective discharge, further research is needed, in particular to assess the influence of the number of flow classes used, as well as different ways of incorporating the available sediment data.

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