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# Dominant discharges for suspended sediment transport in a highly active Pyrenean river

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**Abstract**
*Purpose* Dominant discharges and associated sediment dynamics of the River Isábena, a 445-km$^2$ catchment in the central Pyrenees of Spain that is punctuated by badlands, are analysed.
*Materials and methods* Calculations of suspended sediment loads are based on continuous records of discharge and turbidity obtained at the basin outlet for the period 2005–2010.
*Results and discussion* Dominant discharges for sediment load (i.e. effective discharge) present a bimodal distribution, with one peak falling in the range of low flows and the other associated to less frequent but higher magnitude floods (i.e. bankfull). The highly suspended sediment availability in the badlands, together with the high connectivity between the badlands and the stream network and the important in-channel fine sediment storage, causes both large and small events to remobilize fines. Baseflows, despite their low competence, generate resuspension and massive sediment loads. Thus, effective discharge (i.e. the discharge which transports most of the sediment) is not solely associated with bankfull (i.e. the discharge that dominates channel form), but to a wider range of discharges. Consequently, this river channel is not specifically adjusted to convey most of the sediment load during high floods, as in many other rivers, but instead large volumes of sediment are transferred downstream at an almost constant rate.
*Conclusions* Results suggest that dominant discharge may play a lesser role in terms of (suspended) sediment load in non-supply-limited fluvial systems and/or in rivers that permanently work close to, or at, full transport capacity, as is the case of the Isábena.

**Keywords** Bankfull · Dominant discharge · Effective discharge · River Isábena · Sediment duration curves · Suspended sediment

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## 1 Introduction

The concept of dominant discharge and its relation to the bankfull and effective discharges have been a hot spot of discussion in fluvial geomorphology for several decades, especially since Wolman and Miller (1960) introduced it. Previously, Inglis (1941) had indicated that it is the discharge that controls the meander length and breadth of a river. Definitions have remained somewhat ambiguous and have been modified and refined over time (Ferro and Porto 2012). In any case, the study and understanding of dominant discharge are still necessary because they enable fluvial geomorphologists and hydrologists to better elucidate the relationships between streamflow, channel shape and form, along with sediment transport. It is also important for the design of channels for environmental enhancement and the ecological restoration of rivers, as these require an understanding of long-term channel stability (e.g. Shields et al. 2003). They should also be considered when predicting the stable slope upstream of grade control structures like bed sills and check dams (Porto and Gessler 1999; Ferro and Porto 2011) which are widely used in catchments yielding high sediment loads to retain the sediment—despite the fact that they may have side effects such as inducing channel erosion downstream (e.g. Romero-Diaz et al. 2007; Boix-Fayos et al. 2008)—and for designing moderate to large hydraulic structures (e.g. Brodilov 1996). Stable stream configuration is essentially dependent on the channel's ability to convey the amount of sediment supplied from upstream, with neither net erosion nor aggradation of streambed and banks (Lenzi et al. 2006). Within this context, the dominant discharge has been frequently considered as the discharge that both conveys most of the river's load (i.e. effective discharge) and controls channel form, and it has traditionally been associated with the bankfull discharge. Moreover, dominant discharge is currently used for many other applications, such as quantification of channel maintenance flows, assessment of watershed disturbances, evaluation of flow regulation schemes for rivers and support stream restoration (Bledsoe et al. 2007; Klonsky and Vogel 2011).

Bankfull discharge ($Q_b$) is the maximum discharge that a channel can convey without overflowing onto its floodplain (Wolman and Miller 1960); morphologically, it is very significant because it represents the boundary between channel and floodplain formation processes (Lenzi et al. 2006). It is commonly determined as the elevation of the active floodplain and the maximum elevation of active channel bars (Wolman and Leopold 1957), the height of the lower limit of perennial vegetation (Schumm 1960) and the height of changes in vegetation composition and distribution (Leopold 1994). It can be also determined analytically (i.e. geomorphologically based approach) by the elevation at which the width/depth ratio of a typical cross section is at a minimum (Pickup and Warner 1976). Although all of these methods are useful, their calculation is quite controversial due to subjectivity, and none can be used alone to obtain reliable results (Williams 1978), especially in rivers with irregular cross-sectional depths, in which identifying the value of dominant discharge via $Q_b$ clearly fails (Ferro and Porto 2012). Based on different studies, a discharge of a return period of 1.5 years can be taken as a good proxy of bankfull discharge (i.e. Dury et al. 1963; Leopold et al. 1964; Hickin 1968; Dury 1977; Dunne and Leopold 1978; Harman et al. 1999; Castro and Jackson 2001; Ma et al. 2010).

In turn, effective discharge ($Q_e$) was originally defined as the discharge (or a range of discharges) that is capable of transporting the largest portion of sediment load in the long term (Wolman and Miller 1960). This definition also incorporates the principle of magnitude–frequency of sediment-transporting events, in which the channel-forming discharge could be identified as the maximum of the product of the flow frequency and sediment transport curves. It is originally calculated by applying a sediment-rating curve to determine discharge intervals. As in the case of $Q_b$, the main problem in the determination of $Q_e$ relates to the subjectivity in its calculation, depending on the rating curves and flow frequency distribution used (Nash 1994), the minimum length of the database (Crowder and Knapp 2005) or the number of flow classes used (Sichingabula 1999; Crowder and Knapp 2005). Consequently, large differences in $Q_e$ duration can be found in the literature, varying from the 0.03 % of the time (Sichingabula 1999) to up the 92 % (Ma et al. 2010).

Several studies have attempted to relate both discharges ($Q_b$ and $Q_e$) so as to examine which one is the real dominant discharge, for both form and load, noting significant differences between them (e.g. Benson and Thomas 1966; Ashmore and Day 1988; Whiting et al. 1999; Gomez et al. 2007; Quader et al. 2008). The usual method for doing this is by studying the ratio between $Q_e$ and $Q_b$, but it tends to diverge from unity with the magnitude of large, infrequent events (Wolman and Miller 1960; Pickup and Warner 1976; Nolan et al. 1987; Whiting et al. 1999; Simon et al. 2004). Several researchers have indicated that flow events of a single recurrence interval cannot be considered to be representative of effective or bankfull discharge for all streams because discharge values are influenced by various factors, such as basin morphology, drainage area, hydrologic regime and sediment transport mode (bed load or suspended sediment load) (Ashmore and Day 1988; Nash 1994; Whiting et al. 1999; Phillips 2002; Lenzi et al. 2006; Ma et al. 2010).

While a significant amount of the literature has been devoted to the calculation and definition of dominant discharge, none of these deal with basins exhibiting large amounts of suspended sediments and high amounts of fine-grained in-channel storage. This is the case of the River Isábena, a 445-km$^2$ Pyrenean catchment, which drains extensive areas of badlands and whose sediment production is greater than its transport capacity, resulting in large accumulations of fines along its main channel and tributaries (e.g. López-Tarazón et al. 2011; Buendia et al. 2013). As a consequence, large sediment inputs together with in-channel sediment storage complicate the interpretation of downstream sediment yields and dynamics in terms of sediment source and availability, by attenuating the record of sediment delivery from hillslopes and sediment transfer within the upstream drainage basin (as per Walling et al. 1998). This paper aims to assess dominant discharges (i.e. $Q_b$ and $Q_e$) of the River Isábena for the period 2005–2010, paying special attention to the relations between these discharges and the run-off and suspended sediment dynamics observed during the study period.

## 2 The basin

The Isábena is a mesoscale mountainous catchment (i.e. 445 km$^2$) located in the southern central Pyrenees, NE Iberian Peninsula (Fig. 1a). The River Isábena, together with the Ésera,

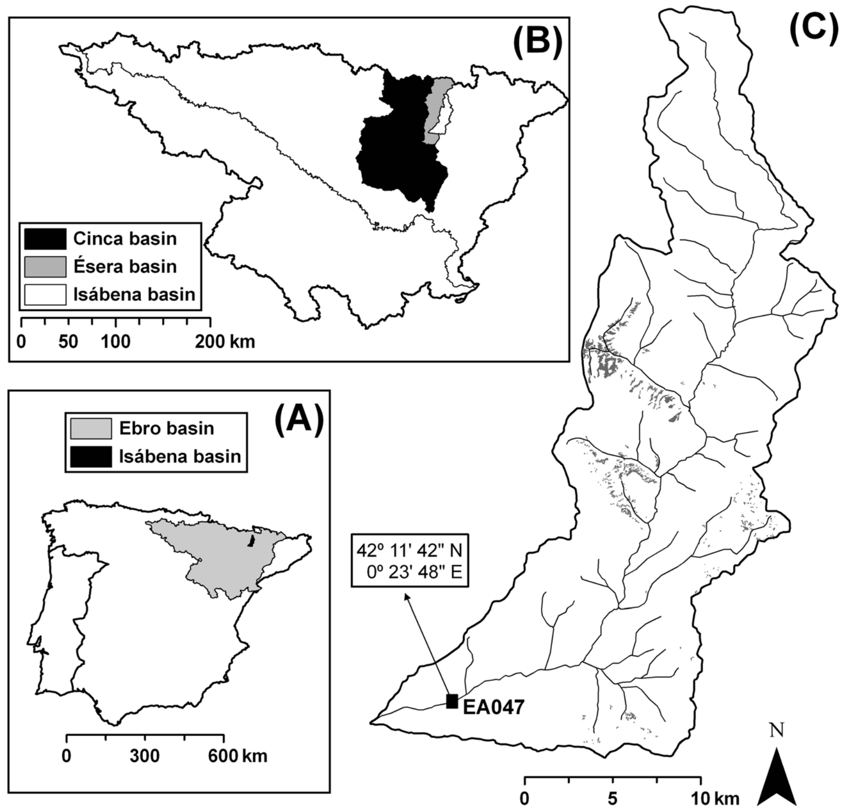



**Fig. 1** **a** Location of the Isábena catchment within the Ebro basin in the Iberian Peninsula, Spain. **b** Location of the Cinca, Ésera and Isábena catchments in the Ebro basin. **c** General map of the Isábena catchment, showing locations of the main badland formations (grey areas) and the location of the gauging station EA047

is one of the main tributaries of the Cinca, in turn the second largest tributary of the Ebro (Fig. 1b). The Isábena basin is characterized by heterogeneous relief (i.e. elevation varies from 450 m above sea level (a.s.l.) at the outlet to 2,720 m a.s.l. at the headwaters), vegetation and soil characteristics (i.e. agriculture prevails in the lowlands while forests, shrubland, grassland and bare soil and rock dominate the headwaters and middle areas). The climate is typical of Mediterranean mountainous areas with mean annual precipitation of 770 mm, ranging from 450 in the lowlands to 1,600 mm at high altitudes.

The most particular characteristic of the basin is the strip of Eocene continental sediments which appears in the central reaches and the lowlands (Fig. 1c); these areas consist of easily erodible materials (marls, sandstones), leading to the formation of badlands that have proven to be the major source of sediment within the catchment, despite representing <1 % of the catchment area (Francke et al. 2008; López-Tarazón et al. 2012a). Sediments coming from the badlands lead to instantaneous suspended sediment concentrations (hereafter *SSC*) up to 350 g $l^{-1}$ at the basin outlet (López-Tarazón et al. 2009), generating mean suspended sediment loads >200,000 t year$^{-1}$ (i.e. period 2005–2009). This equates to specific sediment yields of ~450 t km$^{-2}$ year$^{-1}$, which can be considered high in comparison with counterparts of the same size in this and other regions (de Vente et al. 2006; López-Tarazón et al. 2012a).

The hydrology of the basin is characterized by a rain–snow-fed regime. Floods typically occur in spring, due to large frontal precipitation events and, to a lesser degree, snowmelt and, especially in late summer and autumn, as a consequence of localized thunderstorms. Mean annual discharge at the basin outlet is 4.1 m$^3$s$^{-1}$ ($Q_{10}$=2.14 m$^3$ s$^{-1}$ and $Q_{90}$=8.2 m$^3$ s$^{-1}$, where $Q_i$ is the *i* percentile of the discharge distribution). Mean annual water yield is 177 hm$^3$ ($P_{10}$=68 hm$^3$ and $P_{90}$= 259 hm$^3$), a value that represents ~1.5 % of the Ebro basin's total run-off. Minimum flows (~0.20 m$^3$ s$^{-1}$) typically occur in summer, but the river never dries up.

## 3 Data and methods

### 3.1 Discharge and suspended sediment transport

This work is based on discharge and suspended sediment data collected at the official gauging station located at the basin outlet (i.e. EA047, Fig. 1c). Water level is continuously measured at a 15-min frequency and later converted into discharge by means of the water stage–discharge rating curve developed by the authors from direct measurements (for more information, see López-Tarazón et al. 2010; Fig. 2). Suspended sediment is continuously measured as turbidity using a high-range backscattering Endress+Hauser Turbimax WCUS41 (Endress+Hauser AG, Reinach BL, Switzerland) turbidimeter (measuring range attains 300 g $l^{-1}$). A Campbell CR-510 data logger (Campbell Scientific Inc., Logan, Utah, USA) records the turbidity values

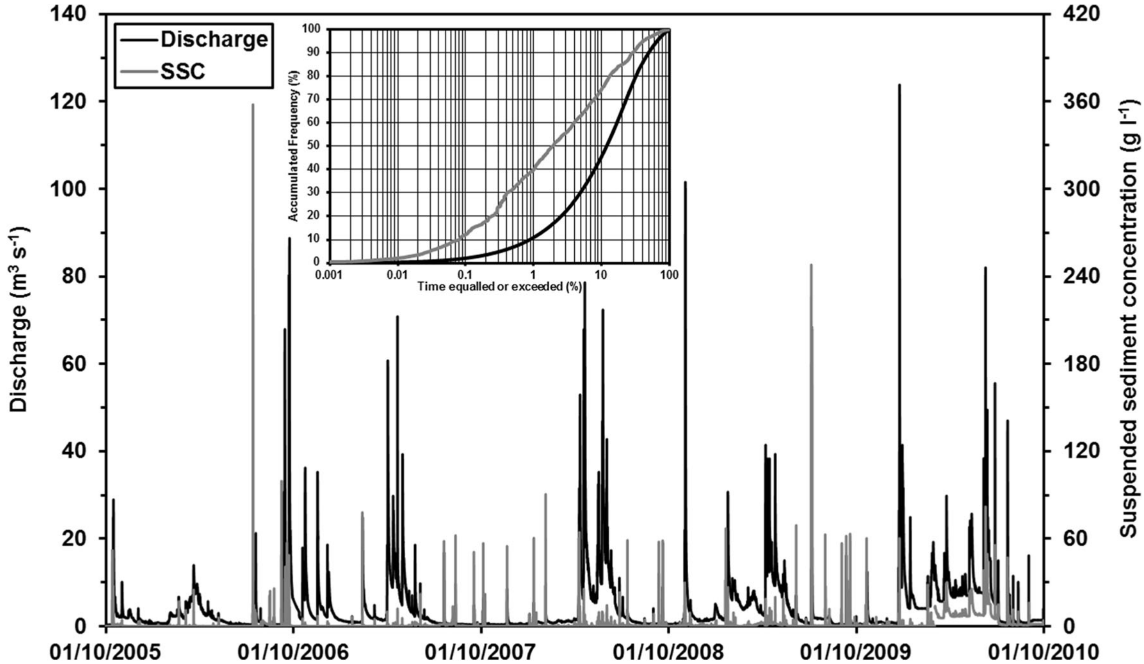



**Fig. 2** Hydrograph and sedigraph of the study period (2005–2010). The *inset* contains the flow and sediment load duration curves obtained based on 15-min measurements for the whole study period

every 15 min from averages of 5-s instrument readings. Turbidity records have been calibrated by means of SSCs obtained from water samples (for full details, see López-Tarazón et al. 2009; Fig. 2). Finally, topographical surveys were undertaken using a dGPS Leica Viva GS15® (Leica Geosystems AG, Heerbrugg, Switzerland) at several reaches close to the outlet for the $Q_b$ determination; topographical observations were post-processed by using the Leica GeoOffice® (Leica Geosystems AG, Heerbrugg, Switzerland) software; hydraulic variables were calculated by means of the software WinXSPRO® (US Forest Service, Fort Collins, Colorado, USA).

Suspended sediment load (hereafter *SSL*) was obtained by multiplying the 15-min SSC (i.e. transformed from the turbidity record, for more details, see López-Tarazón et al. 2009) to the associated discharge value. This was done for the whole study period (2005–2010). From these data and subsequent results, flow and sediment load duration curves were obtained (Fig. 2); both curves were constructed with accumulated percentage of the water yield and sediment load as X ordinates, and the percentage of time each fraction of flow and/or sediment was equalled or exceeded as the Y ordinates.

### 3.2 Determination of effective and dominant discharges

Effective discharges ($Q_e$) for suspended sediment transport, together with the bankfull discharge ($Q_b$), have been determined. The determination of $Q_e$ is somewhat arbitrary regarding the selection of classes used in the analysis, as there is no general agreement on the correct method of determining it (e.g. Sichingabula 1999). Thus, several $Q_e$ were obtained following the approach of Crowder and Knapp (2005). In order to determine the number of classes objectively, the discharge range was divided by a pre-determined class interval size (Johnson 1984; Hays 1988); in this way, an analysis on the sensitivity of $Q_e$ to the size of $Q$ class intervals could be done subsequently. Thereby, the discharge range was subdivided into seven non-overlapping arithmetic and equal size class intervals: (i) 0.5 $m^3\ s^{-1}$ generating 250 groups of $Q$; (ii) 1 $m^3\ s^{-1}$, 125 groups; (iii) 2 $m^3\ s^{-1}$, 63 groups; (iv) 2.5 $m^3\ s^{-1}$, 50 groups; (v) 5 $m^3\ s^{-1}$, 25 groups; (vi) 7.5 $m^3\ s^{-1}$, 18 groups; and (vii) 10 $m^3\ s^{-1}$, obtaining 12 groups of $Q$. The duration (relative frequency) of flows of each class was obtained from the 15-min $Q$ record measured at EA047. Finally, Crowder and Knapp (2005) used the average measured sediment rate for each $Q$ class; in this study, we used the real sediment rate for each $Q$ class obtained from the continuous turbidity series. Thus, the total suspended load transported for each $Q$ class was obtained by multiplying the 15-min $Q$ by the real sediment transported during each $Q$ time (i.e. continuous record approach; i.e. Tena et al. 2011). $Q_e$ was then determined as the mid-point of the discharge class transporting the greatest portion of the SSL (Pickup 1976).

In addition, complementary $Q_e$ for suspended sediment transport was calculated: (i) specific effective discharge (hereafter $Q_{es}$), which is the discharge that optimizes the suspended sediment transport per unit of time (i.e., the discharge with the highest transport capacity); (ii) effective discharge for the maximum *SSC* (hereafter $Q_{eSSCmax}$), which is the discharge that transports the highest instantaneous *SSC*; and (iii) effective discharge for the mean *SSC* (hereafter $Q_{eSSCmean}$), which

**Table 1** Calculated discharges and their definition (see text for more information)

| Discharge | Definition |
|---|---|
| Effective ($Q_e$) | Discharge which transports the largest portion of the suspended sediment load |
| Specific effective ($Q_{es}$) | Discharge that optimizes the suspended sediment transport per unit of time |
| Effective $Q$ for the maximum $SSC(Q_{eSSCmax})$ | Discharge that transports the highest punctual suspended sediment concentration |
| Effective $Q$ for the mean $SSC(Q_{eSSCmean})$ | Discharge that transports the highest mean suspended sediment concentration |
| Bankfull ($Q_b$) | Discharge at which river channel flow just fills the channel to the top of the banks |
| 1.5-year flow event ($Q_{1.5}$) | Discharge of the flow event with 1.5 years of return period |
| 2-year flow event ($Q_2$) | Discharge of the flow event with 2 years of return period |
| Half-load $Q$ ($Q_{1/2}$) | Discharge above and below which half of total sediment load is transported over time |

is the discharge that transports the highest mean *SSC*, considering all the *SSC* of the class interval. All these effective discharges were also obtained for the seven different $Q$ class intervals.

Besides $Q_e$ and all its complementary forms, the dominant discharge for channel form was also estimated. As indicated, the concept of dominant discharge is somewhat controversial. It seems logical to define it as the discharge that over long periods transports the most sediment—i.e. $Q_e$ (Benson and Thomas 1966)—but also one which plays an important (or dominant) role in forming and maintaining a stream's morphology (Crowder and Knapp 2005). Some authors consider bankfull ($Q_b$) as the dominant discharge (Dunne and Leopold 1978); several others support this and have approximated $Q_b$ to the discharge of the 1.5- or 2-year flow event ($Q_{1.5}$, $Q_2$; Dury et al. 1963; Williams 1978; Castro and Jackson 2001; Simon et al. 2004). More recently, others have introduced new indices, such as the half-load discharge ($Q_{1/2}$), which is defined as the discharge above and below which half of the total sediment load has been transported over time (Vogel et al. 2003; Klonsky and Vogel 2011). All such discharges ($Q_b$, $Q_{1.5}$, $Q_2$, and $Q_{1/2}$) have been also calculated for the Isábena. Values of $Q_{1.5}$, $Q_2$, and $Q_{1/2}$ were obtained from the continuous record of discharge and sediment transport at EA047, while $Q_b$ was estimated in a natural non-altered section located ca. 500 m upstream the EA047 by measuring its channel geometry with a dGPS and later determining its minimum width to depth ratio, which theoretically defines $Q_b$ (Wolman 1955; Pickup and Warner 1976). As a summary, Table 1 shows the different discharges together with their definitions.

## 4 Results and discussion

### 4.1 Flow and sediment transport dynamics

As reported by López-Tarazón et al. (2009, 2010, 2012a, b), the run-off and *SSL* transported by the River Isábena are very variable through time, mainly depending on rainfall and the location of the fine sediment along the river network (López-Tarazón et al. 2011). Water yield ranged from 83 to 183 $hm^3$, averaging 128 $hm^3$ (coefficient of variation (CV)=28 %) for the whole study period (Table 2), a low value if compared with the historical mean (177 $hm^3$). In turn, *SSL* varied from 83,200 to 438,300 t, representing an annual specific sediment yield of 187 and 985 t $km^{-2}$, respectively (Table 2). The mean annual value for the study period was 266,900 t, i.e. 600 t $km^{-2}$ (CV=57 %) (Table 2), values that can be considered as high if compared with catchments of similar size in the region (de Vente et al. 2006; López-Tarazón et al. 2012a). Finally, suspended sediment concentrations were also highly variable, ranging from 78 to 358 g $l^{-1}$ (CV=60 %), in the case of the maximum values, and from 0.55 to 1.45 g $l^{-1}$ (CV=37 %) in the case of the mean annual values (Table 2).

Run-off and *SSL* show distinct duration patterns throughout the study period (Fig. 3). Although it is rather constant through time (a particular characteristic of this river), sediment load is still controlled by flood events. Discharges smaller

**Table 2** Summary of water flow and suspended sediment calculations at the EA047 gauging station for the study period 2005–2010 (loads are presented by hydrological years)

| Year | WY[a] ($hm^3$) | SSL[b] (t) | $SSY_s$[c] ($tkm^{-2}$) | $SSC_{max}$[d] ($gl^{-1}$) | $SSC_{mean}$[e] ($gl^{-1}$) |
|---|---|---|---|---|---|
| 2005–2006 | 83 | 185,100 | 416 | 358 | 1.21 |
| 2006–2007 | 118 | 83,200 | 187 | 78 | 0.55 |
| 2007–2008 | 120 | 218,000 | 490 | 90 | 0.74 |
| 2008–2009 | 134 | 409,900 | 921 | 248 | 1.45 |
| 2009–2010 | 183 | 438,400 | 985 | 199 | 0.97 |
| 2005–2010[f] | 128 | 267,000 | 600 | 195 | 0.99 |

[a] Water yield

[b] Suspended sediment load

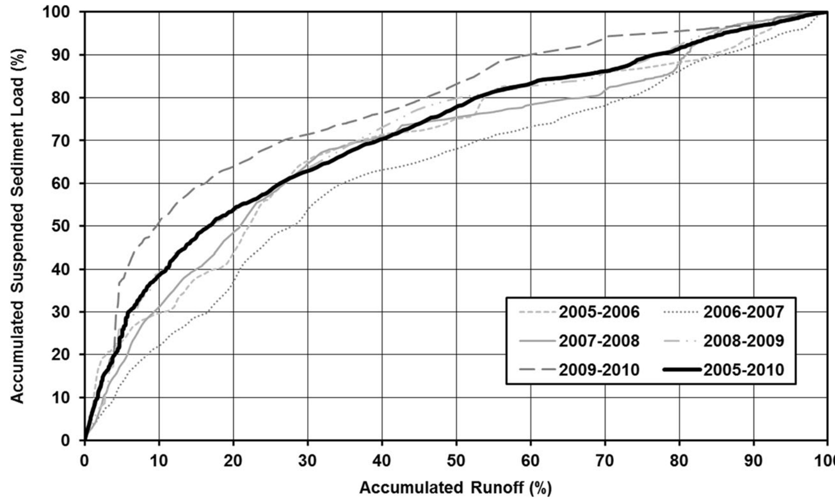
[c] Specific suspended sediment yield

[d] Maximum suspended sediment concentration

[e] Mean suspended sediment concentration

[f] Average value for the study period

Fig. 3 Suspended sediment load and runoff duration for the different years and the whole period




than the median flow (i.e. 4 $m^3\ s^{-1}$, $\sigma$=6.4 $m^3\ s^{-1}$) are responsible for ca. 10 % of the *SSL*, while 50 % of the *SSL* is transported during flows >22 $m^3\ s^{-1}$; this discharge (e.g. five times higher than the mean discharge for the whole period) is equalled or exceeded 17 % of the time (Fig. 3). Nevertheless, values differ for the different hydrological years; 50 % of the *SSL* during 2006–2007 was transported by a discharge equalled or exceeded 27 % of the time, whereas during 2009–2010 (i.e. the wettest year; Table 2), it was transported by flows equalled or exceeded only 9 % of the time (Fig. 3). Differences in the pattern of *SSL* can be better seen in the case of the 90th percentile of the load that is transported by discharges equalled or exceeded 77 % of the time, taking into account the whole study period, but ranging from 60 % in 2009–2010 to 87 % in 2006–2007 (Fig. 3). Runoff pattern is even more regular in time with 50 % of the water yield transported by flows equalled or exceeded 13 % of time (ranging from 8 % in 2007–2008 to 19 % in 2009–2010).

For reference, values in the Isábena are compared with those obtained in basins of the same region and of similar size with available suspended sediment records (Fig. 4; Table 3): (i) the Tordera (894 $km^2$, Catalan Ranges), a typical Mediterranean mountainous stream (three monitoring sites, i.e. Lower Tordera, Upper Tordera and Arbúcies; Batalla et al. 2005); and (ii) the Ribera Salada, a perennial stream located in the Catalan Pre-Pyrenees (one monitoring site, 224 $km^2$) which flows into the Segre River at the Rialb Reservoir (Vericat and Batalla 2010). None of them, including the Isábena, are regulated by dams. The *SSL* duration curve of the Isábena sits between the Upper Tordera and the Ribera Salada (Fig. 4), while it departs from the other Tordera sites, located in the dry lowlands of the catchment. Comparisons are best related to the climatic characteristics of these two groups of basins. Episodic floods (taken here as discharges equalled or exceeded 10 % of the time) typical of the Mediterranean region control between 85 and 95 % of the sediment in the Tordera, while the percentage falls to 70–75 % for the Pyrenean basins (i.e. Isábena and Ribera Salada). Despite differences in magnitude (i.e. in fact, they represent extremes in absolute load terms in the whole Ebro basin), these two

Fig. 4 Comparison between suspended sediment load duration of different river basins in the Pyrenean-Mediterranean region: Isábena (period 2005–2010), Tordera (3 sites, 1990–1999) and Ribera Salada (2005–2008)

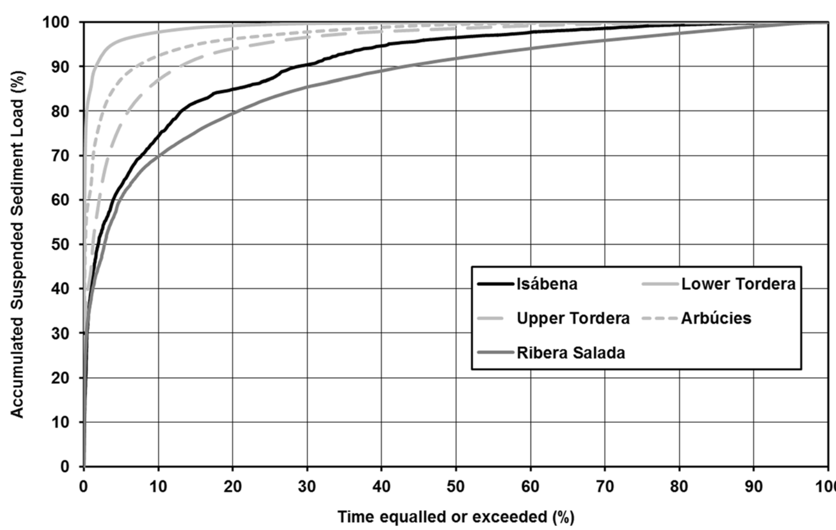


**Table 3** Cumulative suspended sediment load in given percentage of time and by percentage of total discharge in different river basins: the Isábena (period 2005–2010), the Lower Tordera, Upper Tordera and Arbúcies (period 1990–1999) and the Ribera Salada (period 2005–2008)

| River | Area ($km^2$) | 10 % of total cumulative suspended load | | 50 % of total cumulative suspended load | | 90 % of total cumulative suspended load | |
|---|---|---|---|---|---|---|---|
| | | % of time | % of total run-off | % of time | % of total run-off | % of time | % of total run-off |
| Isábena | 445 | 0.08 | 1.7 | 2 | 17 | 29 | 77 |
| Upper Tordera | 35 | 0.01 | 98 | 1 | 99 | 13 | 100 |
| Arbúcies | 106 | 0.01 | 99 | 0.2 | 99 | 7 | 100 |
| Lower Tordera | 785 | 0.005 | 100 | 0.1 | 100 | 2 | 100 |
| Ribera Salada | 224 | 0.05 | 41 | 3 | 80 | 45 | 97 |

rivers indicate the important influence of baseflows on the sediment load. Particularly in the Isábena, one third of the annual sediment load is transported by baseflows (López-Tarazón et al. 2009), a fact that can attributed to the persistence of relatively high discharges during snowmelt from headwaters. This, together with the high availability of sediment in the channel and tributaries of the catchment, favours the constant transport of high loads. Snowmelt also plays a role in the Ribera Salada; this phenomenon, together with the quick exhaustion of sediment readily available to be transported in the channel network during floods, enhances the role of baseflows in the temporal distribution (i.e. duration curves) of the sediment load (Vericat and Batalla 2010).

### 4.2 Effective discharges for suspended sediment transport

A selection of sediment–discharge relations have been plotted (Fig. 5) for the identification of the effective discharge for suspended sediment transport and its derived forms (Table 4). From these plots and from the load duration curves (Fig. 2), magnitude and duration of effective discharges were also determined (Table 4). For each discharge class interval, $Q_e$ and $Q_{es}$ were obtained from the total and specific load histograms, respectively (Fig. 5a, c, e), whereas $Q_{eSSCmax}$ and $Q_{eSSCmean}$ were determined from the maximum and mean SSC curves, respectively (Fig. 5b, d, f). The effects of the selection of the discharge class interval can be easily seen (i.e. different peaks for each effective discharge can be observed in plots where the most detailed class intervals have been used, e.g. Fig. 5a, b); this may add uncertainty in the determination and interpretation of the effective discharge. Conversely, as the class interval increases, and plots simplify, making effective discharge determination easier (i.e. there is just one clear peak for each effective discharge form; Fig. 5e, f). This simplification implies a reduction in the accuracy of the calculation, yielding rather different values for the same effective discharge. In this way, $Q_e$ varies from 3.75 to 9.5 $m^3\ s^{-1}$ (CV=336 %) while $Q_{es}$ ranges from 89 to 124 $m^3\ s^{-1}$ (CV=672 %). In the case of the effective discharge for the SSCs, $Q_{eSSCmax}$ moves from 0.52 to 2.5 $m^3\ s^{-1}$ (CV=166 %) and $Q_{eSSCmean}$ varies from 51 to 124 $m^3\ s^{-1}$ (CV=390 %) (Fig. 6).

These results show that the estimation of effective discharge appears to be very sensitive to the size of class intervals. However, when the size of class intervals is reduced, effective discharge converges on similar values of flow duration (i.e. class intervals 0.5, 1, 2, and 2.5 $m^3\ s^{-1}$; Table 4). Therefore, the smaller the size of class interval is, the more accurate the results are. Nevertheless, among the four smaller class intervals (i.e. 0.5, 1, 2, and 2.5 $m^3\ s^{-1}$), 1 appears to be the most appropriate class interval following the literature. Yevjevich (1972) and Ma et al. (2010) stated that the class interval of flow discharge should not be larger than $S/4$—where $S$ is the standard deviation of flow discharge for the sample (in the case of the Isábena, $S/4$=1.6 $m^3\ s^{-1}$)—even though the number of classes (i.e. 125) exceeds the imprecise number of classes proposed by different authors (between 10 and 25) (Yevjevich 1972; Andrews 1980; Webb and Walling 1982; Sichingabula 1999).

This issue shows that there is not a clear method to calculate effective discharge; it should be evaluated for each catchment independently, in light of many factors such as flow regime, SSC, drainage basin morphology, and size. At 1 $m^3\ s^{-1}$ class interval, $Q_e$ in the Isábena is 9.5 $m^3\ s^{-1}$ (return period, $T$, of 0.6 years estimated from the series of annual maximum discharges for the period 1951–2010 using the Gumbel distribution), characterizing approximately the 50th percentile of the flow duration curve and representing the 77th percentile of the sediment load duration (Fig. 2). At the same interval, $Q_{es}$ is 90.5 $m^3\ s^{-1}$ ($T$=1.8 year), representing the 0.8 and 5th percentile values of the flow and sediment duration curves, respectively (Fig. 2); and, $Q_{eSSCmax}$ is 0.5 $m^3 s^{-1}$ ($T$=0.5 y), and $Q_{eSSCmean}$ is 90.5 $m^3 s^{-1}$, being the 98 and 0.8 percentiles of the flow duration and the 99 and 5 percentile values of the sediment load duration curves, respectively (Fig. 2). These values indicate that $Q_e$ and $Q_{eSSCmax}$ are within the range of low or moderate flows, which implies high flow frequency and small magnitude. For both discharges, and especially for small discharge class intervals (i.e. from 0.5 to 2.5 $m^3\ s^{-1}$), a second peak appears near the 1-year return

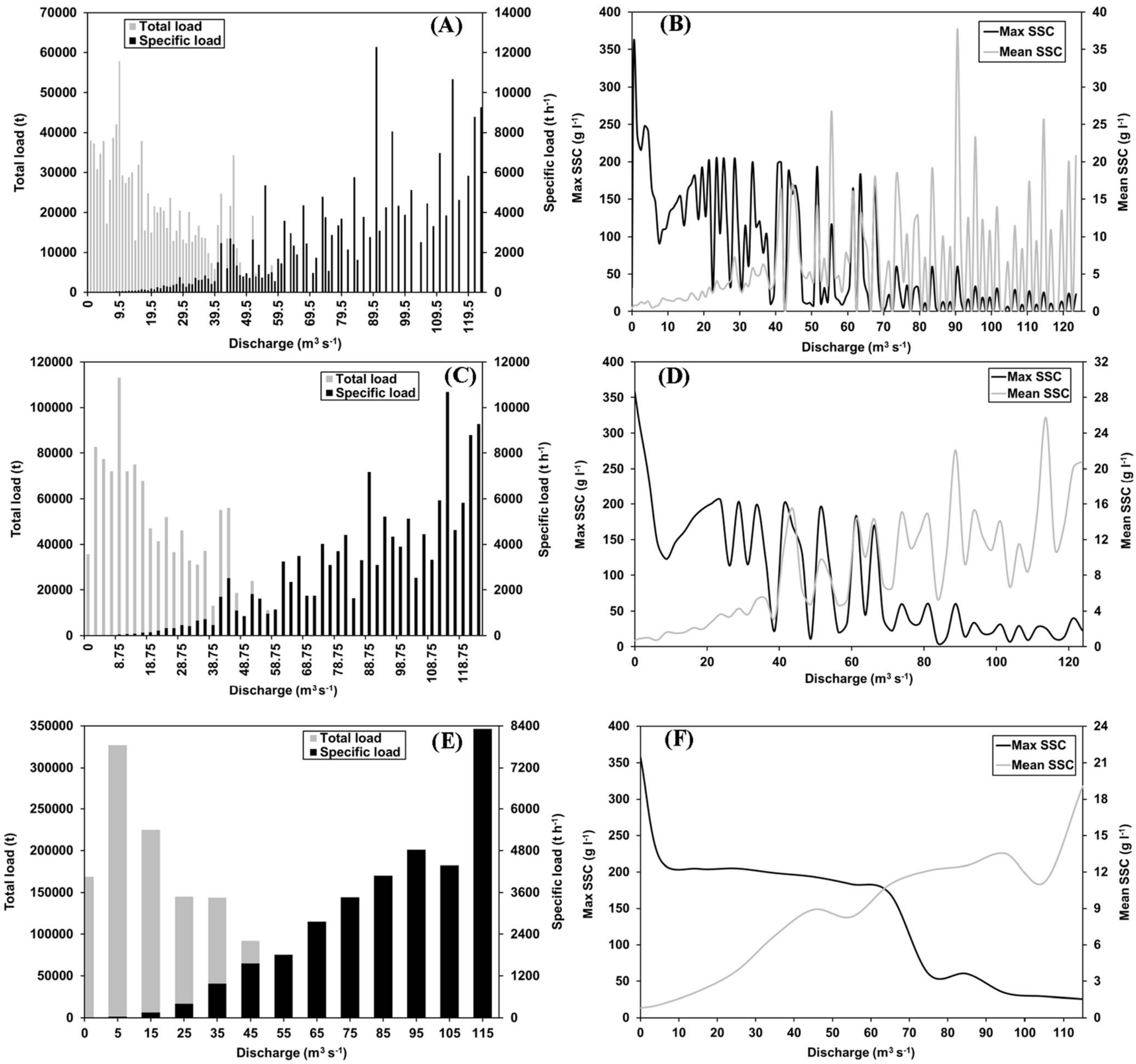



**Fig. 5** Examples of sediment–discharge graphs constructed for the identification of the effective discharge for suspended sediment transport and its derived forms for different class intervals: 1 m$^3$ s$^{-1}$ (**a**, **b**), 2.5 m$^3$ s$^{-1}$ (**c**, **d**) and 10 m$^3$ s$^{-1}$ (**e**, **f**). $Q_e$ was calculated from the total suspended load histogram and $Q_{es}$ from the specific suspended load histogram (**a**, **c**, **e**), whereas $Q_{eSSCmax}$ was calculated from the maximum suspended sediment concentration (SSC) curve and $Q_{eSSCmean}$ from the mean SSC curve (**b**, **d**, **f**)

period event (i.e. 45 m$^3$ s$^{-1}$) that could suggest a bimodal distribution, with one peak on the range of low-moderate flows and another during large floods. This issue emphasizes the importance of the highly suspended sediment availability within the catchment, especially in absolute terms (i.e. total *SSL*, maximum *SSC*), in which not only high events remobilize sediments, but also base and low flows can re-suspend and generate massive loads despite the low competence of the discharges. However, results obtained for $Q_{eSSCmax}$ must be considered carefully as they can be underestimated because of the influence of the highest *SSC* measured in Capella (i.e. 350 g l$^{-1}$), which happened during the recession of a small flood. This could give the low flows more importance than they really have, hiding the role of higher flows. In turn, $Q_{es}$ and $Q_{eSSCmean}$ are within the range of high flows, corresponding to less frequent but higher-magnitude events. Both distributions are clearly unimodal at all discharge class intervals, showing that, in specific terms (i.e. *SSL* per unit of time, mean *SSC*), extremely high events are the ones which transport most of the sediment.

Besides effective discharges, mean dominant discharges (i.e. bankfull-associated *Q*) for four cross sections located

**Table 4** Effective discharge for the different discharge class intervals

| Class interval | 0.5 | | | 1 | | | 2 | | | 2.5 | | | 5 | | | 7.5 | | | 10 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Q$ ($m^3 s^{-1}$) | $f$(Q)[a] (%) | $f$(SL)[b] (%) | $Q$ ($m^3 s^{-1}$) | $f$(Q) (%) | $f$(SL) (%) | $Q$ ($m^3 s^{-1}$) | $f$(Q) (%) | $f$(SL) (%) | $Q$ ($m^3 s^{-1}$) | $f$(Q) (%) | $f$(SL) (%) | $Q$ ($m^3 s^{-1}$) | $f$(Q) (%) | $f$(SL) (%) | $Q$ ($m^3 s^{-1}$) | $f$(Q) (%) | $f$(SL) (%) | $Q$ ($m^3 s^{-1}$) | $f$(Q) (%) | $f$(SL) (%) |
| $Q_e$ | 8.75 | 52.45 | 79.94 | 9.50 | 49.30 | 76.82 | 9.00 | 50.26 | 78.12 | 8.75 | 52.45 | 79.94 | 7.50 | 59.03 | 82.85 | 3.75 | 79.49 | 91.13 | 5.00 | 72.87 | 87.35 |
| $Q_{es}$ | 90.25 | 0.77 | 5.01 | 90.50 | 0.81 | 5.00 | 89.00 | 0.79 | 5.41 | 113.75 | 0.14 | 1.25 | 122.50 | 0.04 | 0.50 | 123.75 | 0.01 | 0.36 | 115.00 | 0.12 | 1.05 |
| $Q_{eSSCmax}$ | 0.75 | 96.66 | 98.95 | 0.50 | 98.24 | 99.63 | 1.00 | 94.52 | 98.11 | 0.63 | 97.35 | 99.31 | 1.25 | 92.72 | 97.33 | 1.88 | 88.30 | 95.94 | 2.50 | 84.01 | 94.01 |
| $Q_{eSSCmean}$ | 51.75 | 3.69 | 18.31 | 90.50 | 0.81 | 5.00 | 89.00 | 0.79 | 5.41 | 113.75 | 0.14 | 1.25 | 122.50 | 0.04 | 0.50 | 123.75 | 0.01 | 0.36 | 115.00 | 0.12 | 1.05 |

[a] Flow duration of effective discharge

[b] Suspended sediment load duration of effective discharge

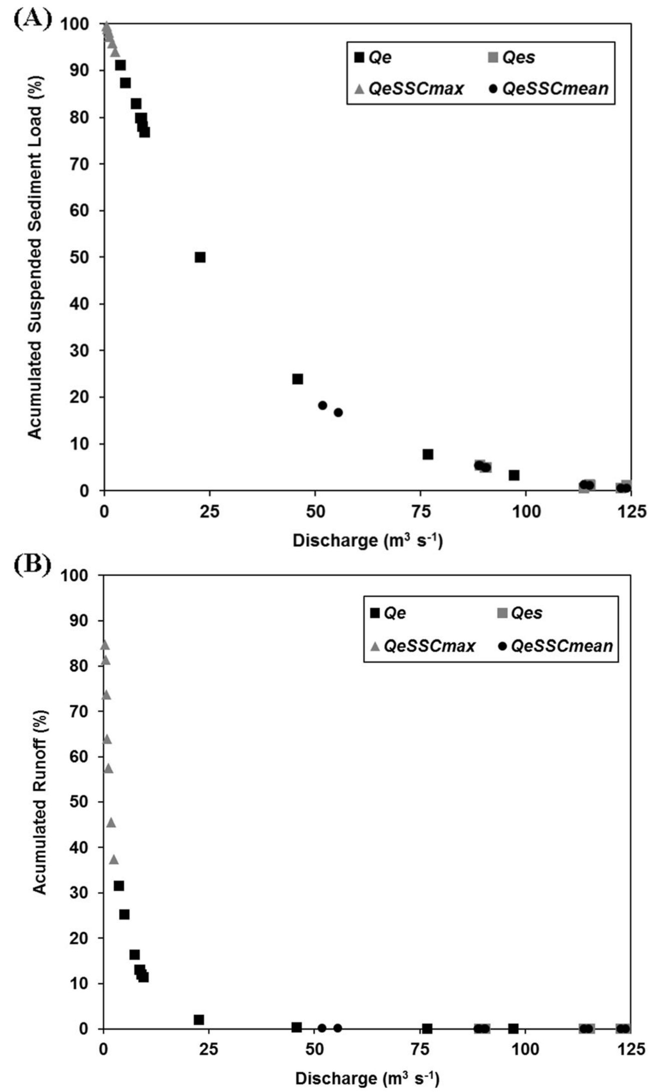



**Fig. 6** Variability of the calculated effective discharges for all the class intervals and its role over the total suspended sediment load (**a**) and runoff (**b**) (see Table 1 and text for information on the abbreviations)

close to the basin outlet were also calculated (Table 5). Within this context, $Q_b$ resulted in 90.4 $m^3 s^{-1}$ ($T$=1.8 years), $Q_{1/2}$ was 22.7 $m^3 s^{-1}$ ($T$=0.7 year), whereas $Q_{1.5}$ and $Q_2$ were estimated at 76.7 and 97.1 $m^3 s^{-1}$, respectively. All values represent a small part of the flow frequency curve, ranging from the 0.02 to 2.24 percentile (Table 5), but despite this, they represent an important fraction of the *SSL* duration load (from 3.34 to 50 %; Table 5). The similarity between $Q_b$ and $Q_2$ indicates that bankfull discharge is reached approximately biannually.

### 4.3 Relations between effective and dominant discharges

The link between effective and dominant discharges is difficult to establish in terms of recurrence interval; nevertheless, following Sichingabula (1999), a realistic comparison

**Table 5** Mean suspended sediment transport dynamics in relation to dominant discharges calculated for four cross sections located close to the Isábena basin outlet (see Table 1 and text for information on the abbreviations)

| | $Q$ ($m^3s^{-1}$) | $f$(Q) (%) | $f$ (SL) (%) |
|---|---|---|---|
| $Q_b$ | 90.43 | 0.03 | 5.08 |
| $Q_{1/2}$ | 22.66 | 2.24 | 50.00 |
| $Q_{1.5}$ | 76.71 | 0.05 | 7.72 |
| $Q_2$ | 97.11 | 0.02 | 3.34 |

between them can be made by calculating a ratio between both (e.g. $Q_e/Q_b$; $Q_{es}/Q_b$). From these ratios (Table 6), it can be seen that $Q_e$ and $Q_{eSSCmax}$ are much smaller than the dominant discharges (ratio between 0.013 and 0.329) whereas $Q_{es}$ and $Q_{eSSCmean}$ are very similar to the dominant ones (ratios very close to 1), especially in the case of $Q_b$ and $Q_2$. This fact may suggest that, in addition to being the flows that control the morphology of the river, $Q_b$ and $Q_2$ (which actually represent almost the same value) seem to have the highest transport capacity in terms of specific load and mean SSC. It also implies that small discharges, located in absolute terms far away from the dominant ones, are the ones controlling the suspended sediment budget by resuspending material and mobilizing large sediment loads. This little agreement between $Q_e$ (understood as the discharge that transports most of the load) and $Q_b$ indicates that the stream channel is not adjusted to its effective discharge or, more precisely, to the range of discharges that transport the vast majority of the sediment load over a period of years. The river channel does not appear to be in equilibrium, and floodplains do not seem to be important for suspended sediment transport in the Isábena basin. Consequently, there is not a balance between erosion and deposition; so, its channel is not formed and maintained by classic cycles of erosion and deposition, scour and fill, as with many other rivers. Hillslopes that are highly connected with the channel, bank erosion and in-channel fine sediment availability represent unlimited sources of sediment that is transported while there is run-off in the river, regardless of run-off magnitude and of the particular form of the channel.

**Table 6** Ratios between the average of the effective discharges and the dominant discharges (see Table 1 and text for information on the abbreviations)

| Dicharge | Ratio |
|---|---|
| $Q_e/Q_b$ | 0.083 |
| $Q_e/Q_{1/2}$ | 0.329 |
| $Q_e/Q_{1.5}$ | 0.097 |
| $Q_e/Q_2$ | 0.077 |
| $Q_{es}/Q_b$ | 1.177 |
| $Q_{es}/Q_{1/2}$ | 4.695 |
| $Q_{es}/Q_{1.5}$ | 1.387 |
| $Q_{es}/Q_2$ | 1.096 |
| $Q_{eSSCmax}/Q_b$ | 0.013 |
| $Q_{eSSCmax}/Q_{1/2}$ | 0.054 |
| $Q_{eSSCmax}/Q_{1.5}$ | 0.016 |
| $Q_{eSSCmax}/Q_2$ | 0.013 |
| $Q_{eSSCmean}/Q_b$ | 1.116 |
| $Q_{eSSCmean}/Q_{1/2}$ | 4.452 |
| $Q_{eSSCmean}/Q_{1.5}$ | 1.315 |
| $Q_{eSSCmean}/Q_2$ | 1.039 |

## 5 Summary and final remarks

Dominant and effective discharges are important concepts in fluvial geomorphology that have been examined and debated for decades. In this paper, we have calculated effective discharge (in its various forms) for suspended sediment transport and dominant discharges (bankfull-associated flows) in the River Isábena basin for the period 2005–2010. First, it is worth emphasizing that large differences have been detected between effective discharges (i.e. $Q_e$, $Q_{es}$, $Q_{eSSCmean}$, $Q_{eSSCmax}$) as a function of the discharge class selected and the data chosen to make calculations, varying from 0.52 to 124 $m^3\ s^{-1}$. It appears that $Q_e$ decreases when discharge class increases, contradicting results previously reported (e.g. Lenzi et al. 2006), but corroborating results obtained by others (e.g. Sichingabula 1999). In the case of the Isábena, this is due to the unusually relevant role that base and average flows (including low-magnitude floods) have on the SSL, conveying huge amounts of fines during the year. Increasing the discharge class inevitably implies giving more importance to single flood events, a fact that may bias total load calculations. Table 4 indicates that a real reduction of $Q_e$ is not seen until the discharge class is increased up to 7.5 $m^3\ s^{-1}$. Consequently, a given flood event (no matter how big its peak discharge was) transporting the highest sediment load for whatever reason (e.g. mud flow, bank collapse) may become the $Q_e$, although it is not totally representative of the temporal distribution of the river's load. As stated by Sichingabula (1999), "the tendency of $Q_e$ stabilising towards the event-based value […] suggests that perhaps it was not necessary to divide the discharge range into classes in order to accurately determine the effective discharge". The question of which is the correct effective discharge thus remains unanswered, and there may not exist a unique, universal method to estimate the effective discharge. Thus, this has to be evaluated independently for each catchment, in the light of factors such as flow regime, SSCs, drainage basin morphology and size.

Dominant discharges have been also calculated; they also display notable variation, with the exception of the bankfull and the 2-year discharges. By comparing effective and dominant discharges, the specific discharge (that optimizes the load per unit time) and the related $Q_{eSSCmean}$ have proven to be similar to bankfull, which by definition is the discharge that controls the morphology of the river. This result also illustrates the role of large events in controlling sediment transport which, in specific or relative value terms (i.e. *SSL* per unit of time, mean *SSC*), represent the most important part. However, $Q_e$ also shows the importance of low to moderate flows in transporting sediment in non-supply-limited systems such as the Isábena (e.g. where badlands are directly connected with the stream, and where substantial in-channel sediment storage exists); in absolute terms, this type of flow controls the sediment yield of the river. Overall differences between $Q_e$ (understood as the discharge which transports most of the sediment) and $Q_b$ (taken as the discharge that dominate channel form) indicate that the channel of the Isábena is not specifically adjusted to convey most of the load during high floods, since it is (quasi)permanently transferred downstream. Overall, the results of this study suggest that dominant discharges may play little role in terms of (suspended) sediment load in non-supply-limited fluvial systems and/or in rivers that permanently work close to, or at, full transport capacity.

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