A volumetric approach to estimate bed load transport in a mountain stream (Central Spanish Pyrenees)

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Abstract In the Arnás stream (Central Spanish Pyrenees) bed load transport is an important process since the channel is totally armoured with coarse particles (D_{50} = 100 mm). Discharge and suspended sediment transport are continuously measured at the outlet of the catchment. Bed load is retained in a trap located before the weir, though during large floods this system is insufficient. In such cases the trap is overfilled, favouring coarse material accumulation a few meters upstream of the outlet. In order to quantify bed load transport, a 3 m long profilometer was built to survey an 11 m^2 area of bed load accumulation. The volume of bed load transport during each flood is estimated from seven profiles measured every 60 cm. Data from seven events are presented. It is shown that the volume of accumulated material does not depend on flow duration or effective runoff but on the peak flow.

Key words bed load transport; experimental catchment; flow event; profilometer

INTRODUCTION

Bed load processes in headwaters have a significant influence upon downstream river bed morphology. In order to understand channel evolution and fluvial disturbances it is necessary to quantify and to characterize bed load regimes in these areas. Many procedures have been developed in order to measure bed load transport (see Kondolf *et al.*, 2003 for a review) but all of them encounter problems, mainly related to the wide range of the material size distribution and to the high temporal and spatial variability of the bed load transport processes. This variability reflects both variations in the flow conditions and in the supply or availability of bed material (Kellerhals & Bray, 1971; Hayward, 1980; Alvera & García-Ruiz, 2000; Rovira *et al.*, 2005). Since bed load monitoring methods are time-consuming and expensive, a variety of formulae have been developed in order to predict bed load transport under given flow conditions (see Gomez & Church, 1989; Yang & Huang, 2001, for a review). However, all of them are to some extent empirical and none universally accepted. The scarcity of reliable data to test them is one of the main deficiencies at present. In the Arnás experimental catchment, the heterogeneous size of the bed load material makes the measurements and the use of an existing formula difficult. The purpose of this study is to estimate bed load transport at the event scale, using a volumetric approach and to examine relationships between bed load transport and other hydrological variables.

STUDY AREA

The Arnás catchment (284 ha) (Fig. 1) is located in the central part of the Spanish Pyrenees, in the basin of the upper Aragón River, a northern tributary of the Ebro River. The average annual rainfall is about 1000 mm, mostly concentrated in autumn and spring. Mean discharge during floods is above 200 L s^{-1}. The bedrock is Eocene flysh with alternating sandstone and marl layers sloping northward. The orientation of the ravine results in a strong contrast between the south and north facing slopes. In the former there are some old debris flows disconnected from the drainage network. The gentler, north facing slope is characterized by old scars and tongues belonging to deep mass movements, nowadays inactive. The stream channel is totally armoured with coarse material (D_{50} = 100 mm), characterized by tabular shapes according to the Zingg (1935) classification. Bed slopes vary between 2% in the lower part of the stream up to 30% in its upper part. The catchment was totally cultivated until the middle of the 20th century with cereal crops in non-terraced fields. Since then, it has been abandoned and affected by a process of natural plant colonization.

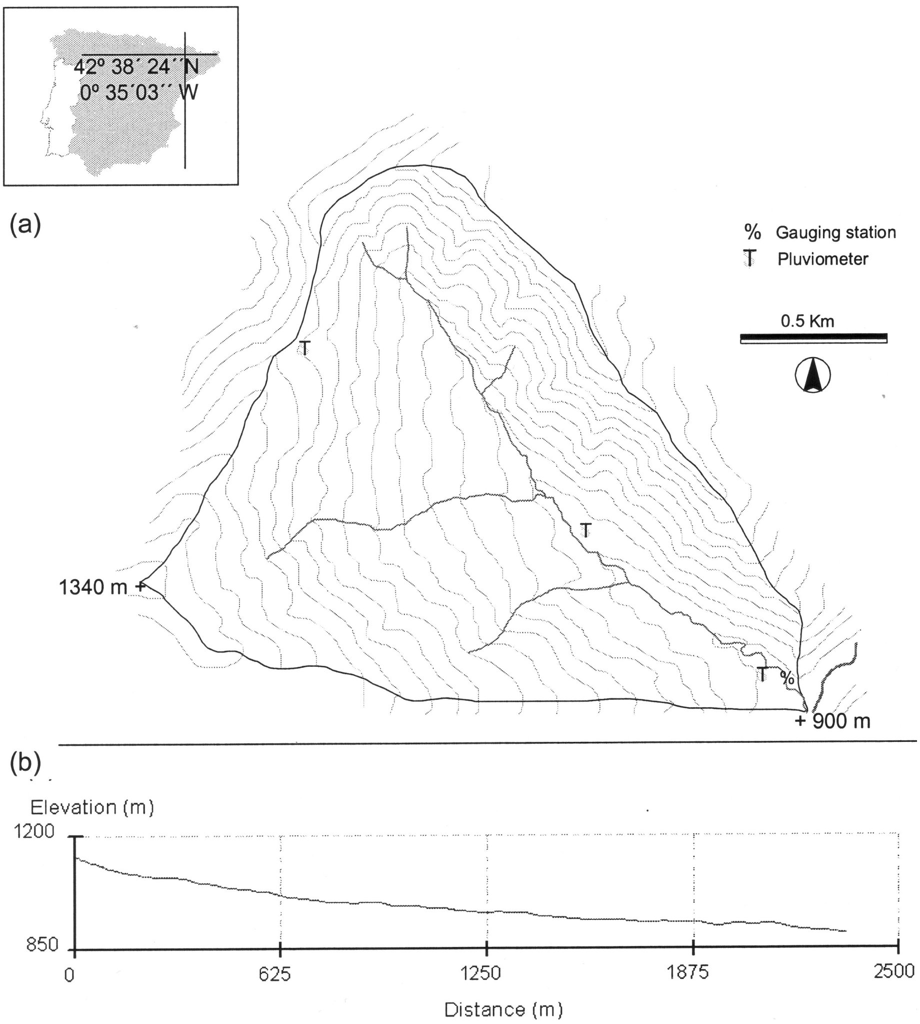

Fig. 1 The Arnás catchment (a) and the elevation profile of the main channel (b).

EQUIPMENT AND METHODS

At the outlet of the catchment a gauging station equipped with an ultrasound water level sensor, an IR turbidity meter and a conductivity meter has been installed. All these sensors are connected to data loggers. After data treatment, continuous series of discharge and sediment transport are obtained. Bed load is retained in a 0.7-m^3 trap located immediately upstream of the flume, though during large floods this system is insufficient. In such cases, the trap is overfilled, favouring the accumulation of coarse material and the creation of a bar in this section of the stream. A 3-m long profilometer was built, capable of being adapted to the river channel morphology (Fig. 2). Twenty sticks were disposed regularly every 15 cm. Seven profiles were measured every 60 cm up the channel so that 140 points are taken over an area of about 11 m^2. A topographic surface is then modelled by the interpolation of the measured points. Considering a clean surface, the volume of the accumulated material (V_b) is calculated and its weight (W_b) estimated (mean specific weight: 2.77 g cm^{-3}). Bed load discharge (Q_b) is defined as the bed load transport rate during effective water discharge. The size of the biggest clast is measured and its weight (W_{bl}) is also estimated. The subsequent removal of the accumulated material facilitates the comparison between events and relationships between bed load discharge and other hydrological variables are analysed. Three metallic baskets, with different screen openings sizes (50 mm, 10 mm, 5 mm), were installed at the exit of the weir in order to ensure, qualitatively, that most of the coarse sediment is retained before the sediment trap. Surface grain size distributions were measured in the study reach by pebble count sampling (Wolman, 1954).

Fig. 2 View of the profilometer in the upper part of the gauging station. Note the coarse size of the accumulated material (September 2003).

RESULTS

It has been found that 50% of the bed material has a grain size larger than 100 mm. Figure 3 shows that the range of the sediment size distribution is very large. Sample

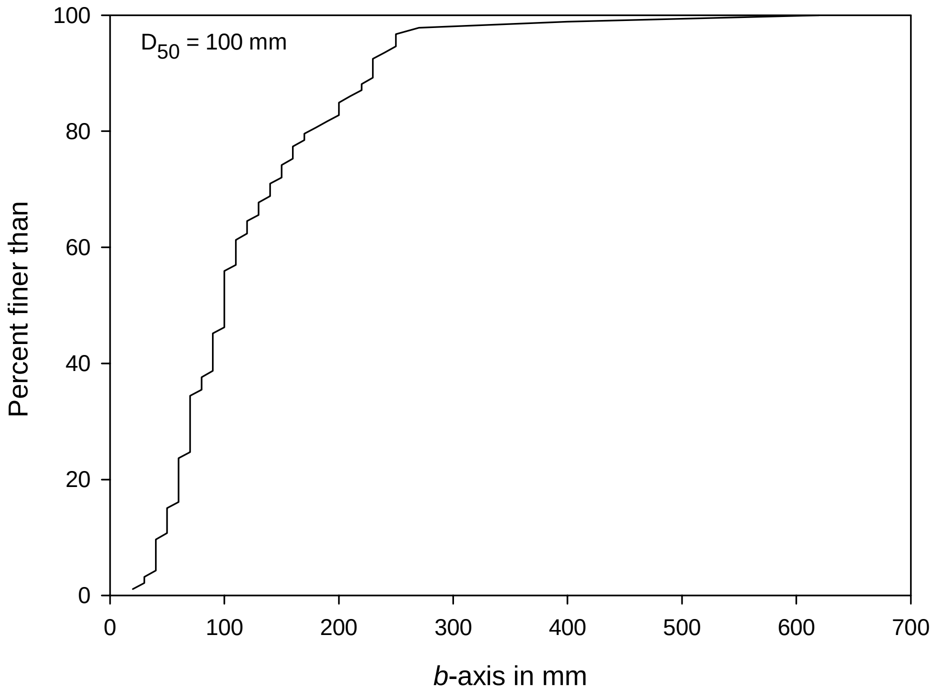

Fig. 3 Grain size distribution of the bed surface material, Arnás stream.

sizes were in the range 20–270 mm except two clasts with *b*-axis equal to 400 and 620 mm. Only 12 events were identified since the first measurement in September 2003 (Table 1). Among them seven were important enough to transport bed load sediment. The few material found within the metallic baskets indicates that the coarser particles (D > 50 mm) are mostly retained before the trap. Data from Table 1 suggest that a threshold of bed load transport can be determined since the maximum discharge without bed load transport is 165 L s^{-1} and the minimum discharge with bed load transport is 580 L s^{-1} (note that these are not definitive values). The heaviest clast displaced weighed 70 kg. Figure 4(a) depicts the relationship between bed load discharge and peak flow, though there is a lack of data across the entire range of flow conditions. Figure 4(b) indicates that bed load discharge does not depend on total runoff, reflecting the relevance of the flow strength. The good relationship between bed load discharge and the peak of suspended sediment (maximum concentration in five minutes) shown in Fig. 4(c) suggests the possibility of using this variable for defining a bed load transport rating curve. However, the use of such information is uncertain since the relationship between turbidity and suspended sediment concentration varies according to the characteristics of the sediment so that measurements made with a turbidity meter are not absolutely reliable (Regüés *et al*., 2002). From the data collected in 2003, Regüés *et al.* (2004) found that bed load corresponds to up to 20% of total sediment load whereas solutes represent 34% and suspended sediment 46%. These values improve some of the results presented in former annual sediment budget studies in the catchment (Arnáez *et al*., 1998). However, they are underestimates since turbidity meters have difficulties in measuring particles over 100 µm in size (Campbell & Spinrad, 1987) and observations indicate that the smaller bed particles (mostly the small-medium gravel fraction) cross the flume.

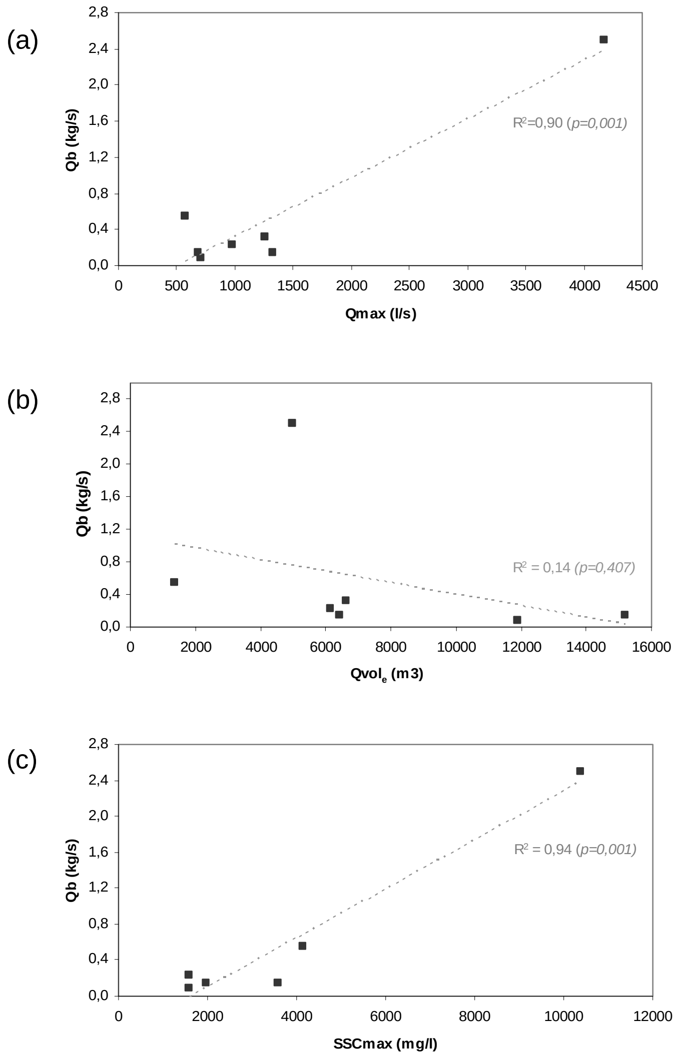

Fig. 4 Relationships between bed load discharge and (a) peak flow, (b) effective runoff and (c) maximum suspended sediment concentration.

Table 1 Characteristics of the analysed events.

Date	Ptot (mm)	IP (mm h^{-1})	Q_e (L s^{-1})	$Qvol_e$ (m^3)	Q_{max} (l s^{-1})	T (min)	T_b (min)	SSC_{max} (mg L^{-1})	V_b (m^3)	W_b (kg)	Q_b (kg s^{-1})	W_{bl} (kg)
06/09/2003	8.8	10.6	–	–	13	290	–	1185	–	–	–	–
07/09/2003	30.8	28.4	1279	4988	4178	390	65	10372	3.5	9750	2.5	70
22/09/2003	12.4	37.2	–	–	13	140	–	576	–	–	–	–
18/12/2003	8.0	2.7	–	–	76	415	–	744	–	–	–	–
28/12/2003	20.4	4.0	238	1357	579	480	95	4147	1.1	3102	0.5	17
17/01/2004	2.6	1.7	–	–	30	210	–	203	–	–	–	–
25/01/2004	16.2	1.6	217	6445	685	1 120	495	1964	1.6	4460	0.2	18
12/03/2004	25.2	2.4	282	11919	712	1 095	705	1591	1.3	3546	0.1	6
28/03/2004	3.3	1.5	–	–	165	270	–	643	–	–	–	–
02/04/2004	11.0	5.5	415	15196	1330	895	610	3589	2.0	5457	0.2	15
30/04/2004	2.2	0.9	320	6135	975	530	320	1591	1.6	4432	0.2	10
22/04/2005	13.8	11.8	408	6614	1263	410	270	–	1.8	5069	0.3	23

P_{tot}, total rainfall; IP, mean rainfall intensity; Q_e, mean discharge during T_b; $Qvol_e$, total runoff during T_b (effective runoff); Qmax, peak flow; T, flood duration; T_b, lag of time for effective water discharge (>165 l s^{-1}); SSC_{max}, maximum suspended sediment concentration in 5 minutes; V_b, volume of bed load accumulation; W_b, weight of bed load accumulation; Q_b, bed load discharge; W_{bl}, weight of the biggest clast.

CONCLUSIONS AND FURTHER RESEARCH

The bed material in the Arnás stream is characterized by coarse particles (D_{50} = 100 mm), even though the range of its size distribution is wide. The presence of very large particles needs to be noted. The volumetric approach for evaluating bed load transport is adequate. The first results have improved the estimations of bed load yield calculated in former studies. Additional data will define thresholds of bed material motion initiation. The first analysis shows that bed load transport is strongly related to peak flow, suggesting: (a) there is a permanent availability of material within the river channel and; (b) bed load transport depends mostly on the flow strength. However, it is necessary to explore if the relationship between bed load discharge and water discharge is defined either by a linear or a power function (Barry *et al*., 2004). Also, the performance of common bed load formulae will be tested in the catchment. All this research will be supported by complementary techniques, i.e. radio transmitters to evaluate travelled distances and displacement thresholds of different clast sizes (Chacho *et al.*, 1989; Ergenzinger *et al*., 1995).

Acknowledgements This research has been financially supported by the following projects: “Hydrological processes in Pyrenean catchments in relation to land-use changes and climatic fluctuations” (PIRIHEROS, REN 2003-08678/HID) and “Modelling hydrological processes in gauged catchments for predictions in ungauged catchments” (CANOA, CGL2004-04919-C02-01/HID), both funded by CICYT, Spanish Ministry of Education and Science, and “Effects of land-use changes on the quality and quantity of the water resources in rural cultivated environments” (CTP, Ref: CTPR10). Monitoring of the catchment has been supported by the agreement between CSIC and the Spanish Ministry of Environment (RESEL). The first author is grateful to the CSIC for financial support within the framework of a I3P PhD grant and to all the people that helped in the removal of the bed material (Ethel Navarro, David Nogués and Eugenio Mingo).

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