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Sediment transport during a flushing flow in the lower Ebro River

RAMON J. BATALLA[1,2], DAMIÀ VERICAT[1,2] & ANTONI PALAU[1,3]

1 *University of Lleida, Av. Alcalde Rovira Roure 177, E-25198 Lleida, Spain*
rbatalla@macs.udl.es

2 *Forestry and Technology Center of Catalonia, Pujada del Seminari s/n, E-25280 Solsona, Spain*

3 *Direction of Environment and Sustainable Development. ENDESA, Carretera de Tarragona km. 89.300 (Magraners), E-25008 Lleida, Spain*

Abstract This study describes the sediment transport which occurred during the double peak flushing flow of November 2003 in the gravel-bedded lower Ebro River (northeast Spain). The experimental release was designed and undertaken to control the excess of aquatic vegetation in the river channel downstream from dams. Macrophytes cause problems to several water users, especially to the hydroelectric and the nuclear power plants located in the vicinity of the river. Observations show a distinct pattern of sediment transport between the two flood peaks owing to the particular channel conditions (i.e. exhaustion of fine sediment and removal of the surface layer). Gravel was mobilized during the flood. However, since bed load rates were low and the flood duration was short, no incision was caused in the river bed. In spite of that, large quantities of macrophytes were removed. The combination of hydraulic and sedimentary parameters during the designed flood maximized the ecological and management benefits of the experimental release without significant adverse geomorphological impacts on the river channel.

Key words dams; Ebro River; flushing flow; macrophytes; sediment transport

INTRODUCTION

Floods are a natural form of disturbance in rivers. They constitute an essential element of the fluvial ecosystem's dynamics and are beneficial and indispensable to the river's normal functioning. By contrast, dams are the elements that most directly alter river flows as they absorb both low flows and flood flows (e.g. Poff *et al.*, 1997) and collect almost all the sediment carried down in the river basin (e.g. Williams & Wolman, 1984). Recovering the natural variability of river flow is thus the basis of sustainable management of regulated fluvial ecosystems. One way of restoring flow patterns altered by dams is to incorporate flushing flows into the management of these types of rivers. A variety of ecological and management objectives for flushing flows can be distinguished, depending on whether they are designed to modify or maintain channel sediment, channel geometry (Kondolf & Wilcock, 1996) or the riverine ecosystem as a whole (Pusey & Arthington, 2003). Methods for estimating the flushing flow needed to keep the substrate in a condition that will support a desired aquatic ecosystem are available (Reiser *et al.*, 1989; Milhous, 1990). The objective of this paper is to report on sediment transport dynamics during a flushing flow undertaken on the lower Ebro River in November 2003, with the purpose of removing the excessive growth of macrophytes in the river channel. Total bed load transport was monitored as a key indicator of river bed dynamics during the experimental release.

STUDY AREA

The Ebro watershed (85 530 km^2) is located in the northeastern part of the Iberian Peninsula (Fig. 1) and has a mean discharge at Tortosa of 450 m^3 s^{-1}. This value represents about 14 300 hm^3 of annual runoff, of which close to 60% is stored in reservoirs (Batalla *et al.*, 2004). Maximum peak flow at Tortosa was estimated at 12 000 m^3 s^{-1} in 1907 (Novoa, 1984). Dams have reduced the magnitude of frequent floods (Q_2–Q_{25}) by 25% (Batalla *et al.*, 2004), trap most of the sediment transported from the upstream reaches (Vericat & Batalla, 2006), and have caused morphological and ecological adjustments to the lowermost reaches of the river (Vericat *et al.*, 2006). The lower Ebro River is a gravel-bed river with a mean slope of 8.5 × 10^{-4}. The bed material consists mainly of gravel and coarse sand. A surface median grain-size of 33 mm was measured in the summer of 2003 at the Móra d'Ebre Monitoring Section (hereafter MEMS) (Fig. 1). The median subsurface grain-size was 21 mm.

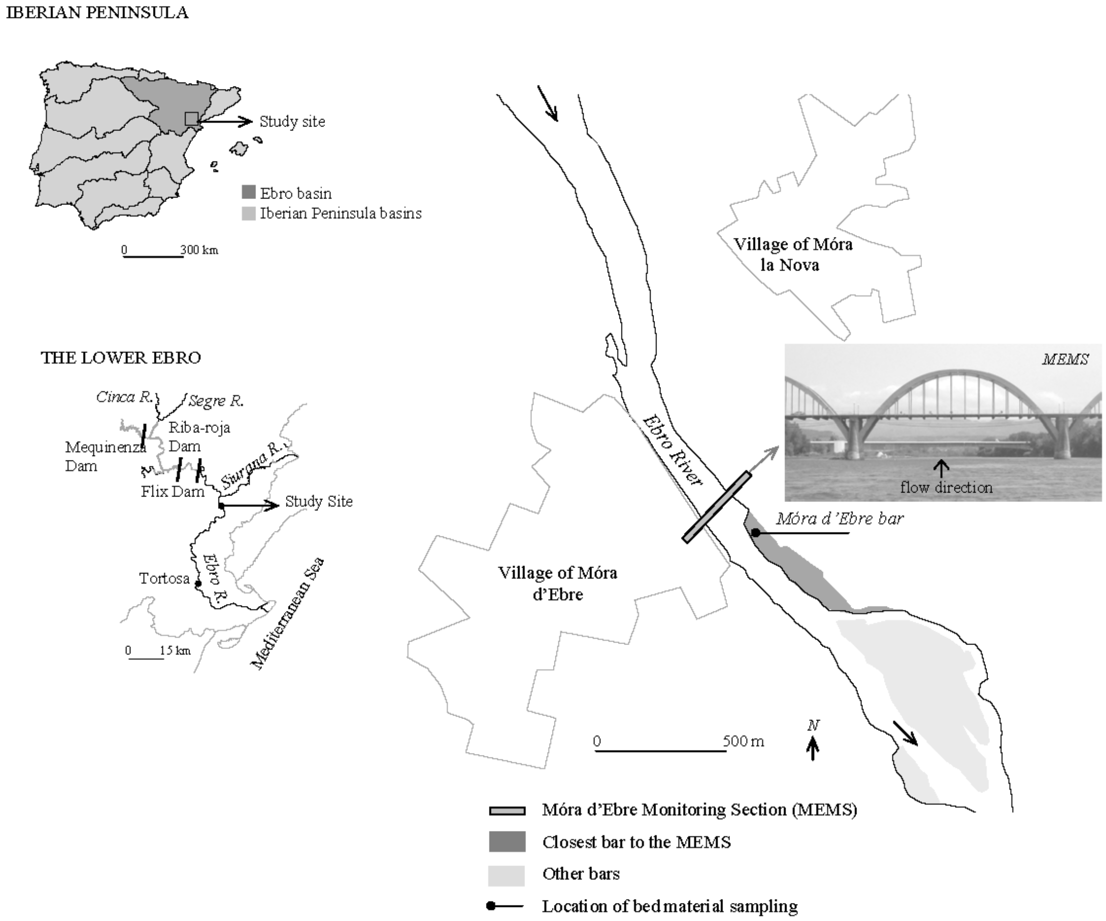

Fig. 1 Location of the study site in the lower Ebro River. The Riba-roja Dam from which the flushing flow was released is indicated.

Abundant macrophyte growth has been observed in the lower Ebro River since October 2001. Almost seven types of aquatic plant species could be differentiated with *Ceratophyllum demersum* and *Potamogeton pectinatus* the most extensive. Macrophyte roots are 80–100 mm long and are generally only present at low water velocities. Persistent low flows, excess of nutrients (nitrogen, phosphorus) and sufficient light availability due to the lack of sediment in suspension are the main causes for the uncontrolled growth of plants in the river bed of the lower Ebro. These plants result in aesthetic, biodiversity and water quality problems and, most important of all, clog the intakes of irrigation, hydropower and nuclear power plants. Macrophytes also produce important impacts on the riverine ecosystem, including retention of suspended sediment and alteration of nutrient cycling and habitat suitability for fish and benthic invertebrates.

FIELD METHODS

Bed load transport was measured at the MEMS, 27 km downstream from Flix, the lowermost dam in the basin (Fig. 1). Bed load was sampled using a 80 kg cable-suspended Helley-Smith sampler with a 152-mm intake. Mean maximum grain-size of the bed load samples were 45 mm, implying that a 152-mm opening Helley-Smith sampler is adequate for most of the grain-size classes that may be encountered during sampling. For more details on sampling procedures see Vericat & Batalla (2006). A total of 36 bed load samples were taken during the flood. They were then dried, sieved and weighed in the laboratory to obtain the total mass and the grain-size distribution. Suspended sediment was sampled by means of a US DH74 depth integrated sampler. Around 1 L of water per sample was filtered to obtain the suspended sediment concentration. Bed load and suspended load were sampled at regular intervals of 30 min over 21 h.

Discharge was estimated by routing hydrographs from the upstream gauging station in Ascó using the Muskingum method, and further compared with discharges recorded at the downstream station in Tortosa (Fig. 1). The actual discharges tended to be systematically overestimated by around 3% (Vericat & Batalla, 2006). The design of the flushing flow was based on the Shields entrainment function, assuming that the mobilization of coarse particles in the river bed causes the removal of most macrophytes that are rooted on it. Hence, water depth was the key parameter used to design the experimental hydrographs.

OBSERVATIONS AND ANALYSIS

An initial flushing flow was released in December 2002 with excellent results in terms of macrophyte removal (Palau *et al*., 2004). The second flushing flow (reported here) was released from the Riba-roja Dam (Fig. 1) over the period 24–25 November 2003. It was designed and monitored by the University of Lleida and ENDESA, the company that operates the hydropower plants in the lower Ebro River.

Flood hydrology

The flood was designed with a double peak, the first aimed at removing the plants and the second at transferring them downstream. Mean discharge during the flood was

~1000 $m^3 s^{-1}$, with two peaks at around 1350 $m^3 s^{-1}$ (Fig. 2). The peak discharge has a recurrence period of 1 year and is equalled or exceeded 10% of time as estimated from the post-dams flow series (Batalla *et al.*, 2004). Maximum mean flow velocity at the MEMS gauging station was 2.2 m s^{-1} with a maximum water depth during sampling of 4.8 m. A total of 76 hm^3 (i.e. 1 × 10^6 m^3) of water were released during the flushing flow.

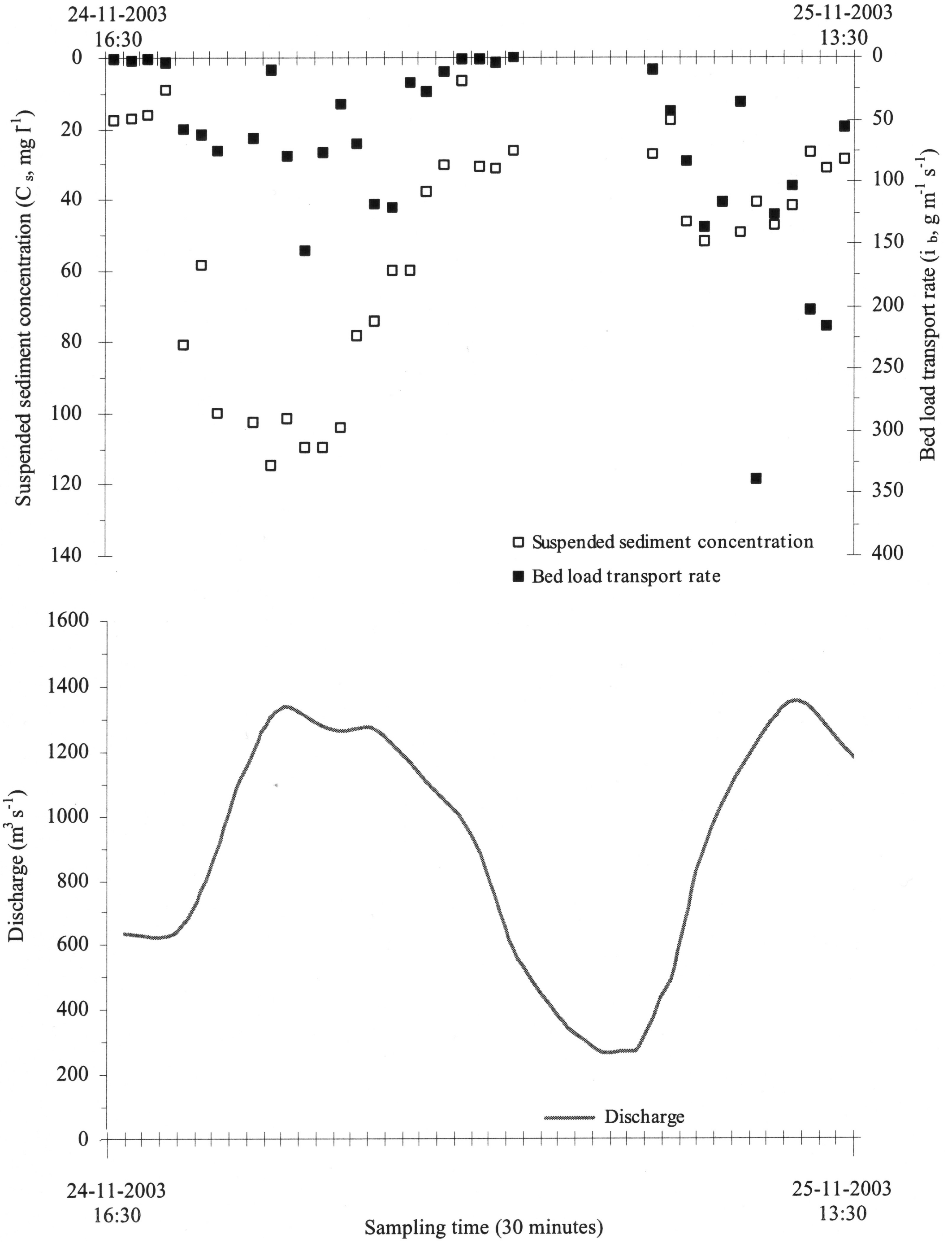

Fig. 2 Hydrograph of the flushing flow of 24–25 November 2003 measured at the MEMS gauging station in the lower Ebro River. Suspended sediment concentrations (C_s) and bed load transport rates (i_b) during the flood are shown.

Sediment transport

Table 1 summarizes the main sediment transport results. Mean suspended sediment concentration (C_S) during the flood ranged from a maximum of 110 mg L^{-1} observed during the first peak discharge to 9 mg L^{-1} obtained during low flows between the peak discharges (Fig. 2). The coefficient of variation was 62%. For comparison, suspended sediment concentrations obtained upstream of the reservoirs during floods of similar magnitude were of the order of 500 mg L^{-1} (Vericat & Batalla, 2006). The relationship between discharge and concentration is statistically significant ($p > 0.99$), although the scatter is high (Fig. 3). The suspended sediment load during the flood has been estimated at around 3236 t at a mean rate of 52 kg s^{-1}. More than 75% of suspended sediment was transported during the first flood peak at a mean rate of 60 kg s^{-1}, owing to the availability of fine material in the surface deposits (see Vericat *et al.*, 2006 for details). Field observations showed a clear exhaustion phenomenon during the second phase of the flood (mean rate of 38 kg s^{-1}, Fig. 2), a fact that can also be related to the lack of fine sediment supplied from upstream reaches.

The mean bed load transport rate (i_b) ranged from a maximum of 340 g m^{-1} s^{-1} obtained just before the second peak of discharge to less than 10 g m^{-1} s^{-1} when the discharge dropped to around 500 m^3 s^{-1} between the two peak discharges (Fig. 2). The coefficient of variation was 100% with bed load rates one order of magnitude higher than those obtained upstream of the dams (Vericat & Batalla, 2006). This reflects a very active river bed with, under present sediment-supply conditions, readily available sediment in bars almost four decades after the dam's closure (Vericat *et al.*, 2006). The relationship between discharge and bed load rate is statistically significant ($p > 0.99$), although the scatter is high (Fig. 4). Total bed load during the flood has been estimated at around 425 tonnes at a mean rate of 7.7 kg s^{-1}. The second flood peak transported 57% of the bed load despite being of shorter duration (33% of the time of the whole flood).

Significant values of bed load were obtained at around 500 m^3 s^{-1} (25.8 N m^{-2}), very close to the critical discharge of 600 $m^3 s^{-1}$ (28.3 N m^{-2}) estimated by means of the Shields function. This fact indicates that river bed material was still rather loose in most of the channel (for more details on the reestablishment of the armour layer during 2003–2004, see Vericat *et al.*, 2006). River bed incision during the flood was negligible, as it was after the 2003–2004 hydrological year (Vericat *et al.*, 2006). This supports the claim that flushing flows can be carried out without significant adverse geomorphological impacts.

Table 1 Mean discharge and sediment transport data during the November 2003 flushing flow at the Mòra d'Ebre monitoring section.

	Discharge [a] (m^3 s^{-1})	Suspended sediment [b] (mg l^{-1})	Bed load [c] (g m^{-1} s^{-1})	$D_{50\text{-}ib}$ [d] (mm)	$D_{max\text{-}ib}$ [e] (mm)
1st flood peak	987	59.9	45.5	16.6	43.0
2nd flood peak	1111	37.6	123.0	18.3	52.9
Total flood	1022	52.3	73.0	17.2	45.1

[a] Estimated discharge at the sediment transport monitoring station.

[b] Mean concentration.

[c] Mean instantaneous transport rate.

[d] Median bed load grain-size.

[e] Maximum bed load grain-size.

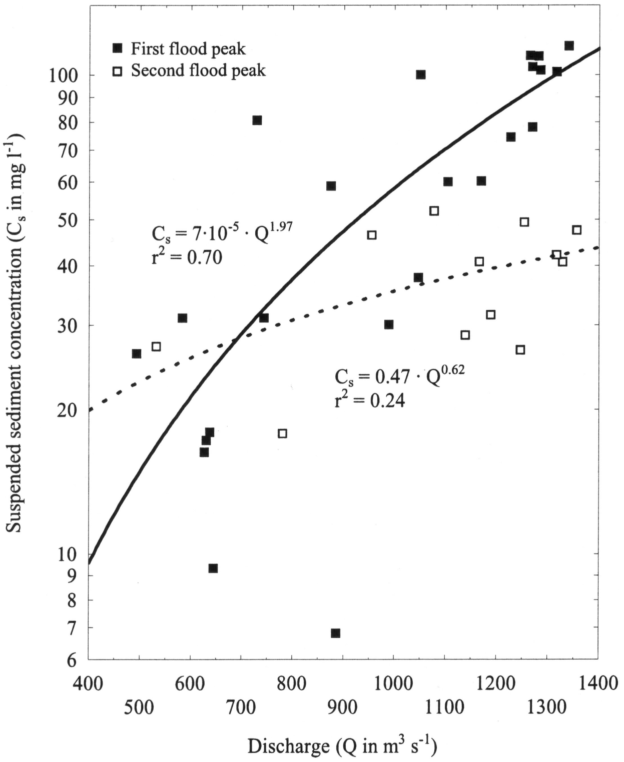

Fig. 3 Statistical relations between discharge (*Q*) and suspended sediment concentration (C_s) for each of the two flood peaks during the November 2003 flushing flow in the lower Ebro River.

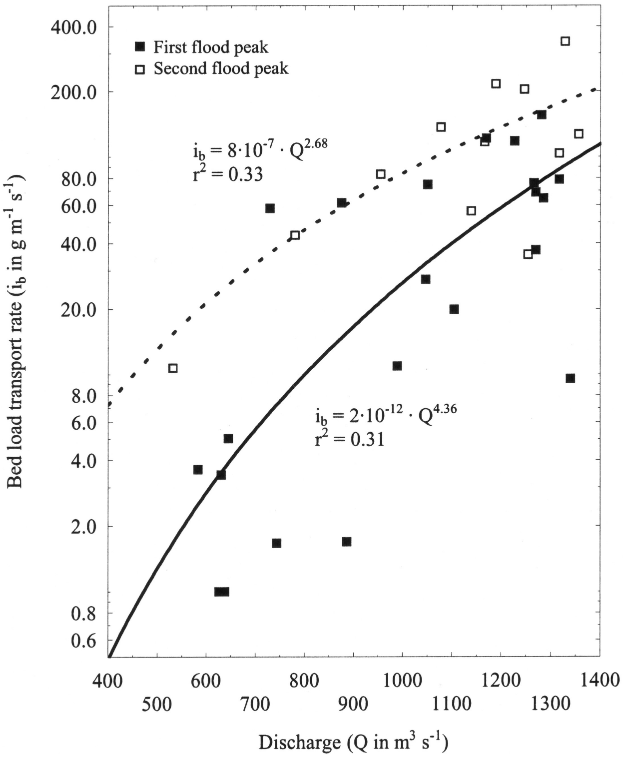

Fig. 4 Statistical relations between discharge (*Q*) and bed load rates (i_b) for each of the two flood peaks during the November 2003 flushing flow in the lower Ebro River.

The median grain size of bed load was 17 mm and ranged from 4 to 40 mm. Mean maximum size was 45 mm, the D_{65} of the surface grain-size distribution. Vericat *et al.* (2006) analysed the mobility of various size classes in the river bed during several floods during the period 2002–2004. Results showed that, on the one hand, particles between 4 and 16 mm were generally over-represented in the bed load during the flushing flow. This suggests a persistent winnowing of those fractions during the flood without replacement from upstream. On the other hand, particles between 32 and 64 mm experienced transport but were under-represented in the bed load. This suggests that the discharges were not competent enough to move those fractions and particles which were hydraulically-limited.

The total solid load during the experimental flood is estimated at around 3660 tonnes, all supplied by the river channel and bed. This value represents around 1% of the river's annual load (2003–2004) and keeps the proportion between suspended (88%) and bed load (12%) observed during that year (Vericat & Batalla, 2006).

DISCUSSION

The main purpose of the November 2003 flushing flow was the removal of the excess macrophytes in the lower Ebro River. The experimental release (i.e. mean annual flood) was designed to mobilize the gravely surface layer of the river, and hence the maximum number of macrophytes anchored into it. In attempting to minimise adverse geomorphological impacts on the river bed (i.e. incision), the design flood used standard estimates of the critical discharge for gravel entrainment, assuming a loose texture of river bed materials and a slight modification of the Shields parameter.

Field observations during and after the flood showed that the greatest quantities of aquatic vegetation were removed and transported downstream in the first few hours of the flood. Fine to coarse gravels were generally mobilized during the flood. However, bed load rates were rather low and, given the short duration of the flood, caused no incision in the river bed. Nevertheless, large quantities of vegetation were removed, maximizing the ecological and management benefits of the experiment. The hydraulic effects of the flood on the density and distribution of vegetation were clearly visible in most areas of the study reach. In all cases there was a general reduction in the quantity of macrophytes on the river bed, and in some areas they practically disappeared. Similar results were obtained during the flushing flow carried out in December 2002 (Palau *et al.*, 2004). Sediment transport information obtained during the flushing flows helps inform restoration actions in the lower Ebro River and may be of use for restoration programmes in other large regulated rivers, especially in the Mediterranean region.

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