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The sediment budget of a large river regulated by dams (The lower River Ebro, NE Spain)

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Abstract
Purpose The aim of this work was to develop a comprehensive fluvial suspended sediment budget for a large regulated river, the lower River Ebro (NE Spain).
Materials and methods The sediment loads of the Ebro mainstem and its main tributaries were estimated from continuous records of water discharge and turbidity (appropriately transformed to suspended sediment concentrations). Records were obtained at ten monitoring sections during the relatively dry 2008–2011 period.
Results and discussion The sediment load estimated for the River Ebro upstream of the Mequinenza Reservoir is remarkable (i.e. mean suspended load of 0.6×10^6 t year^{-1}), despite the fact that the site is already affected by a sediment deficit due to upstream reservoirs. Further downstream, and owing to their humid characteristics, the contribution of the Pyrenean tributaries (Segre and Cinca Rivers) is much larger compared with their Iberian Massif counterparts (Matarranya and Algars Rivers), with sediment loads of 0.49×10^6 and 2,260 t, respectively. The suspended sediment load trapped in the Mequinenza-Ribarroja-Flix Dam Complex for the study period was estimated at 2.3×10^6 t. Below the dams, the sediment load was reduced by 95 % but increased gradually in a downstream direction due to the erosion processes that clear water (i.e. very low sediment concentrations) flood flows exert on the river bed and banks and the episodic contribution from ephemeral tributaries.
Conclusions Reservoirs have reduced the overall sediment load and the natural variability of flow and sediment transport in the River Ebro. In addition, the sediment budget revealed that floods were not the only drivers of the sediment dynamics in the lower Ebro. For instance, the particular location of the monitoring sections showed that episodic contributions from small tributaries alter the general sediment load of the river during certain torrential events.

Keywords Fluvial sediment budget · Reservoirs · River Ebro · Suspended sediment transport

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1 Introduction

A sediment budget is a simplification of the interaction between geomorphological processes that transfer sediment from headwaters, through the fluvial network, to the outlet of the drainage basin (Dietrich and Dunne 1978). This concept provides an effective basis for quantifying and representing the key components of the sediment delivery system within a catchment, such as the fluvial sediment transport component (e.g. Swanson et al. 1982; Batalla et al. 1995; Reid and Dunne 1996; Owens 2005). Sediment budgets can take many forms, and be constructed over several scales, and incorporate various levels of precision (Reid and Dunne 2003). The versatility of the sediment budget concept has allowed its application to solve a wide range of questions. For instance, it has been applied to the study of rates of landform evolution (e.g. Rapp 1960; Harvey 1992) and to the effects of climate change (e.g. Leopold et al. 1964) and changes of land use (e.g. Fredriksen 1970; Janda et al. 1975; Swanson et al. 1982; Page and Trustrum 1997) on catchment geomorphic processes. Also, this concept has been applied to the study of the effects of earthquakes on sediment inputs and transport (e.g. Pearce and Watson 1986; Burbank 1992) and to the effects of human-related activities such as gravel mining (e.g. Collins and Dunne 1989) and dam construction and operation (e.g. Wilcock et al. 1996; Van Steeter and Pitlick 1998; Wohl and Cenderelli 2000) on sediment yields.

The interest in the latter from both scientists and practitioners has increased since the growth of dam construction on most of the world's rivers, particularly the larger ones. Consequently, dams have been recognized as the primary, but not unique, reason for the decreasing trend of land–ocean sediment transfers (e.g. Milliman and Syvitski 1992; Meybeck and Ragu 1997; Walling and Fang 2003; Walling 2006). Vörösmarty et al. (2003) suggested that the overall proportion of the total sediment flux that is trapped in reservoirs is as high as 53 % worldwide. In several recent cases, such as the Yangtze River, China, the reported impacts are well document and widely known. Five years after the closure of the Three Gorges Dam (i.e. June 2003), the sediment discharge decreased drastically from 164 to 9 Mt; only 2 % of its 1950–1960s level (Xu and Milliman 2009). In the case of the Colorado River, USA, the completion of Glen Canyon Dam caused a decrease of about 99.5 % in the amount of fine sediment entering the Grand Canyon. Poulos and Collins (2002) also reported a reduction in the sediment supply to the Mediterranean basin by almost 50 % since the middle of the twentieth century, associated to, among other reasons (e.g. changes in climate and land use), the sediment trapped in reservoirs of large rivers, such as the Po, the Rhône and the Nile. The River Ebro, Spain, is one of those large Mediterranean rivers that have been progressively impounded during the last century; for more details, see Batalla et al. (2004) on the hydrological effects of dams, and Vericat and Batalla (2010) on the changes in sediment delivery due to trapping in reservoirs. Dams located in the lowermost stretch of the river have significantly altered its water and sediment regimes. There are several recent studies on the sediment transport and geomorphic processes in the lower Ebro in relation to dams (e.g. Vericat and Batalla 2006; Tena et al. 2011, 2012a). In such works, quantification of sediment loads at various temporal and spatial scales has been done. However, no comprehensive sediment budget assessment has been undertaken at a more regional scale, i.e. including quantification and analysis of sediment loads from the main tributaries to reservoirs and the sediment delivery from them. Such a sediment budget represents the main aim of the present work. To construct the budget, we have estimated the suspended sediment load for a three year period (2008–2011) at the outlet of each of the main sub-basins that debouch into the Ribarroja Reservoir, as well as at several locations in the lower Ebro between the Ribarroja Dam and Tortosa (the most downstream monitoring section, 40 km upstream from the Ebro delta). The objective of this work was to construct a fluvial sediment budget for the lower part of the basin, highlighting, quantifying and assessing the effects of dams on the magnitude and frequency of the river's sedimentary regime. The assessment of sediment budgets in rivers should be viewed as an important requirement for sound management (Walling 2006) since they provide key insights into the spatial and temporal dynamics and the magnitude of sediment transport processes. Our findings provide useful information to: (1) help understand the sediment dynamics of the lower river reaches since this includes estimations of sediment delivery from the upper River Ebro and the main tributaries; (2) assess the sedimentation in the reservoir complex; and (3) evaluate the sediment deficit in the downstream reaches. This information can be used as the basis for the re-assessment of restoration practices currently undertaken in the lower Ebro (for more details, see Batalla and Vericat 2009).

2 Study area

2.1 The Ebro basin

The River Ebro (Fig. 1a) is the largest drainage basin in the Iberian Peninsula, draining a total area of 85,534 km^2 and accounting for ca. one sixth of its total area. The natural boundaries of the Ebro River basin are the Cantabrian Ranges and the Pyrenees in the north, the Iberian Massif in the southeast and the Catalan Coastal Ranges in the east. The river flows 910 km NW-S, from the Cantabrian Ranges to the Mediterranean Sea, where it forms a delta, an area with some of the most important wetlands in the western Mediterranean region. Due to its large catchment area, the Ebro basin is highly heterogeneous. The basin varies from above 3,400 m above mean sea level in the Central Pyrenees to sea level at the delta (see Fig. 1b). Mean annual precipitation is 600 mm, although seasonal and annual variability may be very high. The rainfall is also irregularly distributed, ranging from more than 2,000 mmyear^{-1} in the upper Pyrenean areas, to 900 mm year^{-1} in the Atlantic headwaters, to 500 mmyear^{-1} in the southern Mediterranean zone and to <300 mmyear^{-1} in the dry interior depression (Fig. 1c; source Ebro Water Authorities (CHE)). Mean annual discharge in Tortosa is 438 m^3 s^{-1} which corresponds to an annual water yield of 13,810 hm^3 (SD= 5,474 hm^3 year^{-1}, where SD is the standard deviation of the

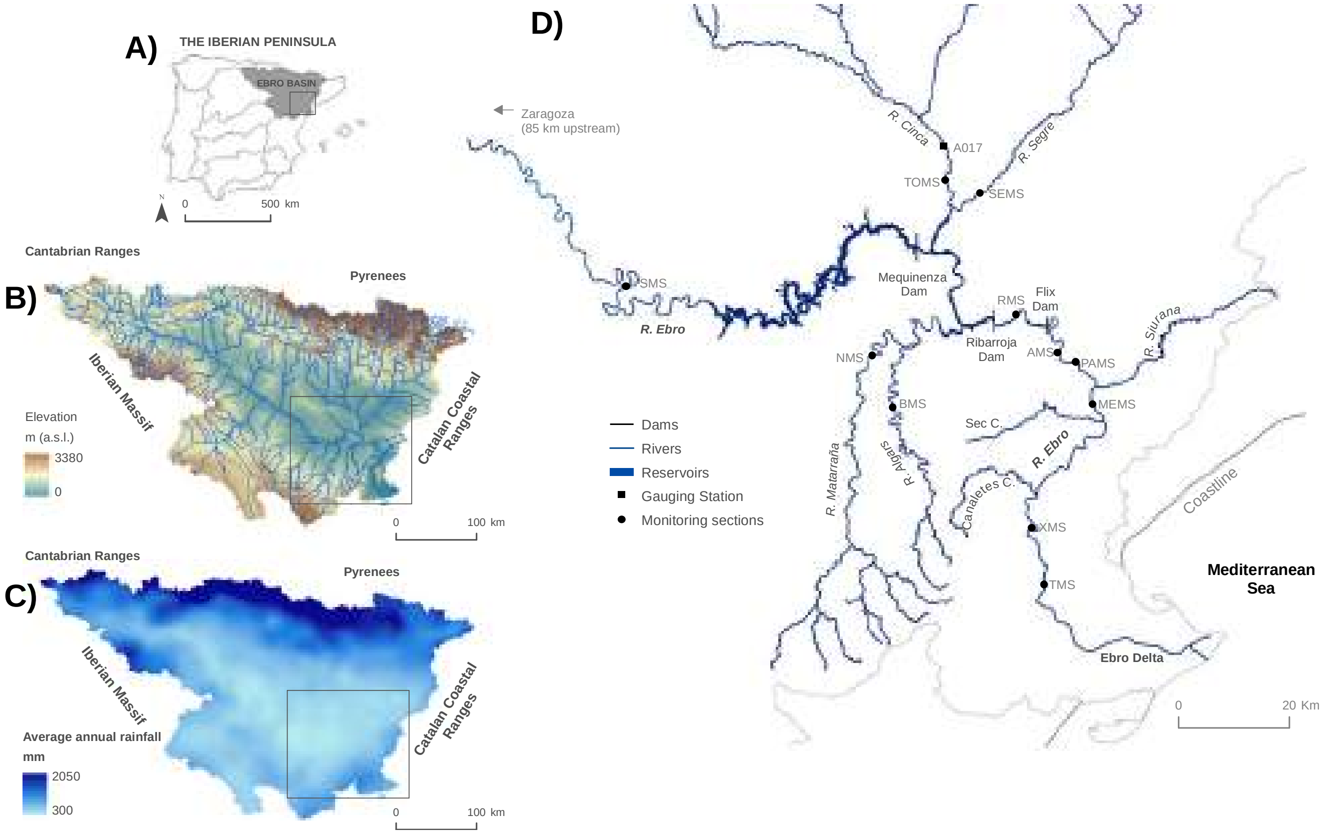

Fig. 1 **a** The River Ebro basin within the Iberian Peninsula, **b** altitudinal distribution of the Ebro basin, **c** rainfall distribution in the Ebro basin, **d** the lower Ebro (area covered by box in (**b**)): river mainstem, main tributaries, main reservoir complex (Mequinenza-Ribarroja-Flix) and monitoring sections. Initials and the complete names of the monitoring sections are: (1) tributaries from the Iberian Massif, i.e. Batea Monitoring Section, River Algars (*BMS*) and Nonaspe Monitoring Section, River Matarranya (*NMS*); (2) tributaries from the Pyrenees, i.e. Torrente Monitoring Section, River Cinca (*TOMS*) and Serós Monitoring Section, River Segre (*SEMS*); (3) the lower River Ebro upstream from the Mequinenza Reservoir, i.e. Sástago Monitoring Section (*SMS*) and downstream from the Ribarroja Dam, i.e. Ribarroja Monitoring Section, Ribarroja (*RMS*), Ascó Monitoring Section (*AMS*), Pas de l'Ase Monitoring Section (*PAMS*), Móra d'Ebre Monitoring Section (*MEMS*), Xerta Monitoring Section (*XMS*) and Tortosa Monitoring Section (*TMS*)

1912–2012 series). Runoff varies substantially, from a maximum annual runoff of 30,821 hm^3 (1914–1915) to a minimum recorded at 4,284 hm^3 (1989–1990). Maximum peak flow was estimated at around 12,000 $m^3 s^{-1}$ in Tortosa in 1907 (Novoa 1984). Nowadays, 187 reservoirs impound around two thirds of the mean annual runoff of the basin. Only 25 of these reservoirs have a capacity of >50 hm^3, and they represent 90 % of the total basin reservoir storage capacity (Batalla et al. 2004). The largest dam chain in the whole basin is located in the lower Ebro and is composed of Mequinenza (constructed in 1966, 1,534 hm^3), Ribarroja (1969, 207 hm^3) and Flix (1948, 11 hm^3) dams (MRFDC), which together impound waters from 97 % of the basin area (see Fig. 1d).

2.2 The lower Ebro and its main tributaries

For the purpose of this study, the lower Ebro is considered as the reach between the Mequinenza Dam (i.e. backwaters of the Ribarroja Reservoir, see Fig. 1d) and Tortosa. Rivers debouching into the Ribarroja Reservoir are the main focus of analysis, although the work also includes the Ebro mainsteam from upstream of the Mequinenza Reservoir. Flow discharge in the River Ebro upstream of MRFDC is characterised by a pluvio-nival hydrological regime, under the influence of the Atlantic climate of the Cantabrian Ranges and the western Pyrenees. It thus presents elevated flows during winter (when the maxima took place, i.e. February) and spring, while low flows are mostly present during autumn and summer, with the minimum in August. The River Ebro upstream from the Mequinenza Reservoir (Sástago Monitoring Section (SMS); see Fig. 1d) drains a basin of approximately 51,210 km^2 and is not extremely regulated yet, and the Ebro Reservoir is the only large reservoir (500 hm^3) upstream of this point (impoundment ratio (IR)=0.59; Batalla et al. 2004).

The main tributaries from the west margin (Pyrenees) are the Segre and the Cinca rivers, while those from the east margin (Iberian Massif) are the Matarranya and Algars. The tributaries flowing from the Pyrenees are the largest (i.e. area, in square kilometres) in the basin and contribute most of the discharge, a fact clearly conditioned by their hydrological regime. The strong effect of snow retention in the central and eastern Pyrenees determines the nivo-pluvial regime, with a maximum in spring and a relatively constant flow in summer.

The Segre and Cinca Rivers are the largest tributaries of the Ebro, draining basins of ca. 12,751 and 9,608 km^2, respectively. Both are regulated by dams, with a total capacity of 1,872 and 837 hm^3 for the Segre and Cinca, respectively (IR=1.31 and 0.49 for the study period, respectively; Batalla et al. 2004). Further south, the Mediterranean tributaries, Matarranya and Algars Rivers, are characterized by a rainfall-based flow regime (i.e. no snow cover), with maxima in spring and autumn and a minima in summer. The total area of the Matarranya basin is 1,717 km^2 of which 405 km^2 correspond to its main tributary, the Algars. A small tributary of the Matarranya River, the River Pena, has a reservoir with a capacity of 17.8 hm^3. Downstream of the Flix Dam, the main tributary is the Siurana River which is heavily altered by dams and gravel mining. Dams have decreased the magnitude and frequency of floods, while mining (located in the lowermost reaches of the river) has drastically reduced the supply of sediment to the Ebro mainstem.

3 Sampling and monitoring

Data used in this study consisted of continuous series of water discharge and turbidity collected at 11 measuring stations in the Ebro mainstem and its main tributaries from 2008 to 2011. The main purpose was the construction of a fluvial sediment budget focused on the Ribarroja Reservoir (for a complete view of location of monitoring sites, see Fig. 1d).

3.1 Discharge

Discharge (Q) measurements have been obtained through three different ways, from: (a) official gauging stations operated by CHE; (b) our own monitoring sections by means of water stage probes; and (c) nonmonitored control sections to which Q has been routed from nearby gauging stations. Details of the three data sources are given below.

(a) Gauging stations operated by CHE are labelled AMS, TMS, BMS, NMS and SEMS (see Fig. 1d for complete names and location details). At these stations, flow stage is continuously recorded by means of an OTT® water stage recorder and transformed into Q using the corresponding h/Q rating relations, maintained by the CHE.

(b) Our own monitoring sections where we record water stage continuously are MEMS and TOMS (see Fig. 1d). At these sections, water stage was measured by means of TruTrack® WT-HR (capacitive water stage sensors with logger) installed at suitable places (e.g. concrete walls). Sensor bias was estimated at 2 %, on average, by comparing direct measurements on a scale and sensor readings during weekly field visits. Flow stage was recorded at 15-min intervals. At these stations, Q was calculated using the stage/area method (i.e. WinXSPRO®). This software application calculates Q by means of Manning's equation, on the basis of topographical information and grain-size distribution data (i.e. grain-size samplings were done at each section) to estimate the roughness coefficient, n. Moreover, in order to corroborate the values obtained by means of the stage-area method, a relation between water stage at MEMS and TOMS and Q obtained in the closest upstream CHE gauging station (i.e. Ascó EA167, AMS, and Fraga EA017, respectively; see Fig. 1d) was established. Once hydraulic parameters (e.g. transit time and Q attenuation) were known, hydrographs from the CHE stations were routed to MEMS and TOMS, following the Muskingum method for the whole data series (i.e. Shaw 1983). Discrepancies between routed hydrographs and modelled Q were <5 % at both monitoring sections. Although the XMS is an official water quality section operated by the CHE, it does not have an official h/Q rating relation. Routing methods have been applied to derive Q from the nearest gauging station (Tortosa, CHE EA27; for detailed information on this particular issue see Tena et al. 2012a).

(c) We have compiled data for monitoring sections where no water stage sensors existed, i.e. RMS, PAMS and SMS (see Fig 1d). At these sections, hydrographs have been directly routed from the nearest gauging stations, also by means of the Muskingum method. At RMS, hydrographs were routed from the Ribarroja Dam, located 3 km upstream, while at PAMS hydrographs were routed from the Ascó gauging station EA163, located 2.5 km upstream (for detailed information see Tena et al. 2011, 2012a). Finally, in the case of SMS, Qs were routed from the Zaragoza gauging station (EA11, located 85 km upstream), as Q does not change significantly between these two sections (for detailed information see Vericat and Batalla 2006).

3.2 Suspended sediment

Turbidity data (as a proxy for suspended sediment concentration (SSC)) have been obtained from two different sources, from: (a) official water quality stations and (b) from monitoring sections equipped with our own turbidity probes (see Fig. 1d for details).

(a) Water quality stations are operated by two different institutions: CHE and the Catalan Water Agency (ACA). Data supplied by CHE (i.e. PAMS and XMS) were recorded every 15 min by means of a Hach® SS6 turbidity probe (0–10,000 nephelometric turbidity units (NTU)), while data supplied by the ACA (i.e. SEMS) were also recorded every 15 min by means of a Campbell® OBS-3+ turbidity probe (0–4,000 NTU).

(b) At our own monitoring sections (i.e. at RMS, AMS, MEMS, TMS, BMS, NMS and TOMS) we recorded turbidity continuously. At these sections, turbidity was measured by means of optical turbidity probes McVann® Analite NEP9510 and NEP9530, according to the turbidity range observed at each section (from 0 to 3,000 NTU in sections upstream from the dams and 0–1,000 NTU in those downstream, where SSCs are typically much lower; Vericat and Batalla 2006). Campbell® data loggers were used to store turbidity values every 15 min averaged from 5-s readings. Hourly means were subsequently derived to smooth short-term variability and to average calculations.

It is worth mentioning that at SMS, annual suspended sediment yield (SSY) was calculated from load-rating relations between Q and SSC using the previously routed hydrograph. A statistically significant Q–SSC relation obtained by Vericat and Batalla (2006) for the hydrological year 2003–2004 (i.e. the most appropriate in relation with the hydrology of our study period 2008–2011) was used to estimate SSC and thus suspended sediment loads (SSL).

As part of the comprehensive suspended sediment sampling program implemented since 2002 in the lower Ebro and its main tributaries, 1-l manual samples were collected intensively during individual flood events and routinely (weekly or fortnightly) during periods of low flows (for more details, see Vericat and Batalla 2006; Tena et al. 2011, 2012a, b). Overall, a total of 1,650 suspended sediment samples were used to calibrate the turbidity data and complement the sediment load calculations. Samples were vacuum filtered by means of glass microfiber filters (Filter-Lab, 0.0012 mm pore size), dried and weighed in the laboratory to determine the SSC (in milligrammes per litre). The content of organic matter (OM) was determined following methods summarised by Tena et al. (2011). Once the OM was determined, it was subtracted from the filter weight. We then established a correlation between the NTU and SSC for each individual probe (i.e. river section). In most cases, the relation followed a linear regression (i.e. $\mathrm{SSC}=a\times\mathrm{NTU}+b$, where a varies from 0.6 to 0.9 and b from −10 to 3.5, with coefficient of determination (i.e. r^2) between 0.89 and 0.98). Only at SEMS, the relation between NTU and CSS followed a relation of the type $\mathrm{SSC}=0.0093\times\mathrm{NTU}^2+1.1303\times\mathrm{NTU}+3.8$ ($r^2=0.96$). Finally, annual sediment load was calculated by multiplying the hourly SSC (in milligrammes per litre) and the continuous Q (in cubic metres per second).

4 Flow regime

The mainstem River Ebro has joined most of its tributaries in the basin, although not the largest ones, before entering the Mequinenza Reservoir (at SMS). At SMS, the flow regime it is not heavily influenced by dams and could be considered as the most *natural* of all the Ebro monitoring sections (in this study). Mean annual water yield at SMS during the 3-year study period was 5,926 hm^3, a value much lower than that registered historically (i.e. 1912–2012, 7,310 hm^3). Thus, the study period can be considered as dry, with its annual water yield exceeded 60 % of the time during the period of record (1912–2012). Mean Q at SMS for the complete study period was 187 $m^3 s^{-1}$ (SD=201 $m^3 s^{-1}$), ranging from 20 to 1,545 $m^3 s^{-1}$ (i.e. the latter value represents a return period of 1.2 years ($Q_{1.2}$), reached during a flood in February 2009. The interannual coefficient of variation (i.e. $\mathrm{CV}=Q_{\mathrm{SD}}/Q_{\mathrm{mean}}$) was 107 %, a value that confirms the higher variability in comparison with other sections in the lower Ebro downstream from the dams.

The River Segre is the largest tributary of the Ebro, and collects water from several large Pyrenean tributaries. A few kilometres before it enters into the Ribarroja Reservoir, the Segre merges with the Cinca, its main tributary. The mean annual water yield at SEMS (River Segre) during the 3-year study period was 1,427 hm^3, a slightly lower value than the 1,676 hm^3 registered at TOMS for the Cinca River. In both cases, runoff is well below historical values (i.e. 5,353 hm^3 $year^{-1}$ in the Segre-Cinca system from 1950 to present), confirming the dry characteristics of the study period. Moreover, the proportion of water yielded from the two basins—45 and 55 % at SEMS and TOMS, respectively—differed from the overall historical relation, which is 55 and 45 %, respectively. The shift in the relative runoff proportion between the two rivers may be related to the recent increment of flow regulation in the Segre (Batalla et al. 2004), a fact that typically favours generalized water losses in the catchment due to diversions and related evapotranspiration from agricultural fields and reservoirs. Mean Q at SEMS for the complete study period was 45 $m^3 s^{-1}$ (SD=36 $m^3 s^{-1}$), ranging from 13 to 498 $m^3 s^{-1}$ (i.e. value that represents a return period of 2 years, Q_2, reached during a spring flood in 2010), while mean Q at TOMS was 53 $m^3 s^{-1}$ (SD=36 $m^3 s^{-1}$), ranging from 15 to 593 $m^3 s^{-1}$ (i.e. $Q_{1.2}$), both registered during the same hydrological year (2009–2010) (Table 1). The interannual coefficient of variation was 79 % at SEMS and 68 % at TOMS. Figure 2a shows that high discharges (i.e. taken here as double the mean Q) represent <7 % of the time in these two monitoring sections, but were responsible for 23 % of the total water

Table 1 River flow data for the study period at the monitoring sections in the lower River Ebro and its main tributaries (see Fig. 1d for exact locations and notations)

Area	Section	Year	Q_{mean} ($m^3 s^{-1}$)	Q_{max} ($m^3 s^{-1}$)	Q_{min} ($m^3 s^{-1}$)	SD ($m^3 s^{-1}$)	Total runoff (hm^3)
Iberian tributaries	BMS	2008–2009	0.5	23.1	0.0	1.0	15.4
		2009–2010	0.2	5.0	0.0	0.4	6.5
		2010–2011	0.4	39.5	0.0	2.0	13.1
		2008–2011	0.4	39.5	0.0	1.3	11.7[b]
	NMS	2008–2009	0.8	32.8	0.2	1.9	26.0
		2009–2010	0.2	3.9	0.0	0.4	7.0
		2010–2011	0.5	49.9	0.0	2.7	14.7
		2008–2011	0.5	49.9	0.0	1.9	15.9[b]
Pyrenean tributaries	TOMS	2008–2009	54.0	230.6	18.3	35.2	1,702.0
		2009–2010	58.7	593.2	15.0	48.2	1,851.3
		2010–2011	46.8	127.4	17.6	17.3	1,475.9
		2008–2011	53.2	593.2	15.0	36.2	1,676.4[b]
	SEMS	2008–2009	58.0	245.3	19.0	30.5	1,829.3
		2009–2010	46.8	498.2	12.8	48.5	1,477.1
		2010–2011	30.9	114.0	13.8	13.7	973.4
		2008–2011	45.2	498.2	12.8	35.8	1,426.6[b]
Ebro mainstem[a]	SMS	2008–2009	234.2	1,544.7	36.9	252.1	7,384.8
		2009–2010	199.0	1476.4	36.5	190.8	6,275.1
		2010–2011	130.7	932.4	19.1	126.6	4,121.1
		2008–2011	187.9	1,544.7	19.1	201.3	5,927.0[b]
	RMS	2008–2009	344.3	1,259.5	1.8[c]	251.3	10,859.4
		2009–2010	314.1	2,028.3	0.8[c]	198.7	9,904.9
		2010–2011	214.9	1,123.1	1.5[c]	119.5	6,775.7
		2008–2011	291.1	2,028.3	0.8[c]	205.0	9,180.0[b]
	AMS	2008–2009	358.4	1,110.7	118.1	213.0	11,303.8
		2009–2010	349.0	1,321.2	118.4	211.5	11,004.9
		2010–2011	235.4	1,236.9	118.9	114.3	7,423.2
		2008–2011	314.3	1,321.2	118.1	193.7	9,910.6[b]
	PAMS	2008–2009	351.3	1,088.4	115.8	213.0	11,101.2
		2009–2010	342.0	1,294.8	116.1	211.5	10,801.8
		2010–2011	230.7	1,212.2	116.5	114.3	7,213.4
		2008–2011	308.3	1,315.9	115.8	189.8	9,705.5[b]
	MEMS	2008–2009	340.7	1,055.8	112.3	213.0	10,878.2
		2009–2010	331.7	1,256.0	112.6	211.5	10,590.8
		2010–2011	223.8	1,175.8	113.0	114.2	7,016.4
		2008–2011	304.2	1,310.7	118.1	187.9	9,495.1[b]
	XMS	2008–2009	319.0	1,109.9	106.3	218.8	10,078.6
		2009–2010	313.8	1,327.3	99.0	221.6	9,908.6
		2010–2011	214.2	1,011.4	88.1	135.6	6,819.0
		2008–2011	282.8	1,305.4	88.1	205.7	8,935.4[b]
	TMS	2008–2009	312.7	1,088.1	104.2	218.8	9,860.6
		2009–2010	307.6	1,301.3	97.1	221.6	9,701.6
		2010–2011	210.0	991.6	86.3	135.6	6,621.0
		2008–2011	276.8	1,301.3	86.3	201.7	8,727.8[b]

SD standard deviation, *BMS* Batea Monitoring Section, River Algars, *NMS* Nonaspe Monitoring Section, River Matarranya, *TOMS* Torrente Monitoring Section, River Cinca, *SEMS* Serós Monitoring Section, River Segre, *SMS* Sástago Monitoring Section, *RMS* Ribarroja Monitoring Section, Ribarroja, *AMS* Ascó Monitoring Section, *PAMS* Pas de l'Ase Monitoring Section, *MEMS* Móra d'Ebre Monitoring Section, *XMS* Xerta Monitoring Section, *TMS* Tortosa Monitoring Section

[a] Sections ordered following the river course

[b] Mean value

[c] Minimum values when the Ribarroja Dam was closed

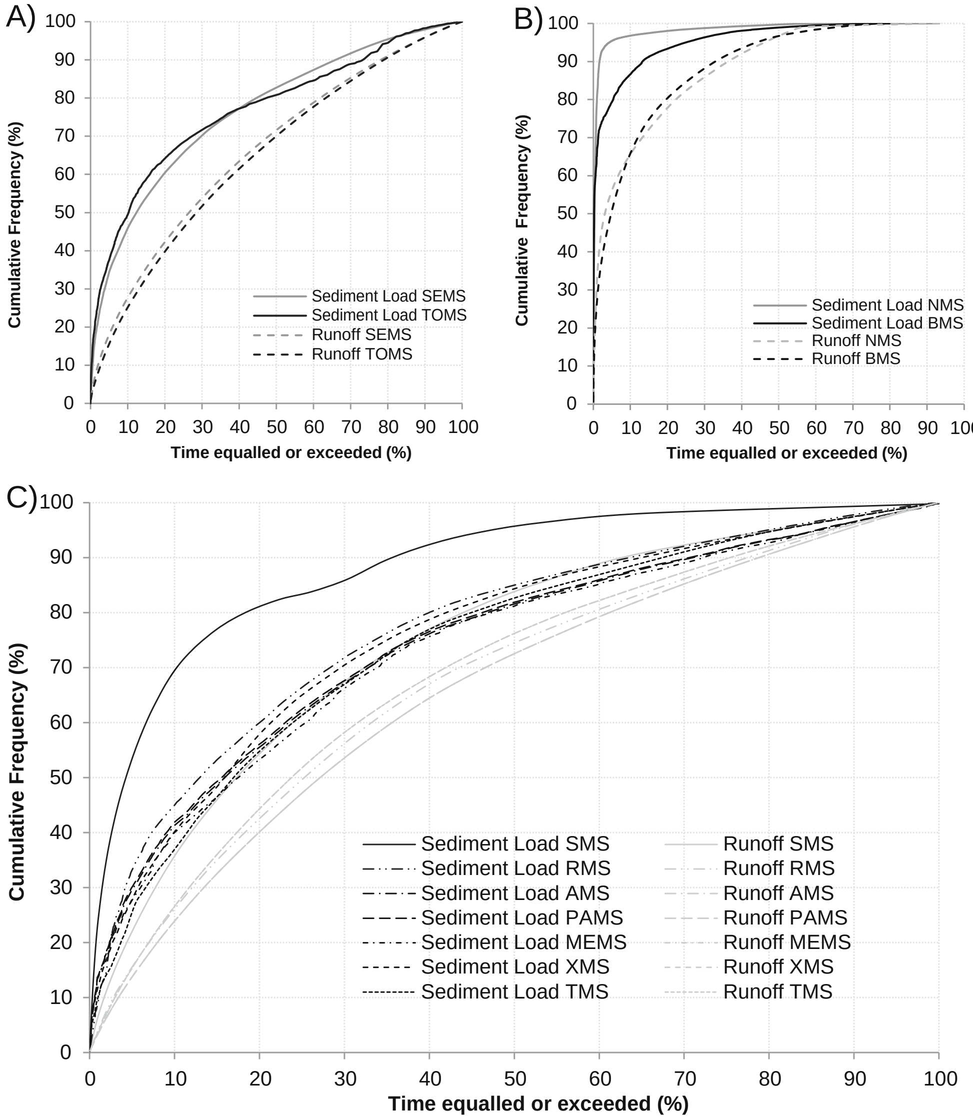

Fig. 2 Suspended sediment load and runoff frequency curves of the monitoring sections for the study period (2008–2011). Curves are grouped according to their geographical location: **a** tributaries from the Iberian Massif, i.e. BMS (River Algars) and NMS (River Matarranya); **b** tributaries from the Pyrenees, i.e. TOMS (River Cinca) and SEMS (River Segre); and **c** the lower River Ebro upstream from the Mequinenza Reservoir, i.e. SMS (Sástago) and downstream from the Ribarroja Dam, i.e. Ribarroja (*RMS*), Ascó (*AMS*), Pas de l'Ase (*PAMS*), Móra d'Ebre (*MEMS*), Xerta (*XMS*) and Tortosa (*TMS*). See Fig. 1d for location details

yield at SEMS and 20 % at TOMS. Discharges respectively equalling or exceeding 50 and 90 % of the time were responsible for 72 and 95 % of the total water yield in SEMS and 70 and 96 % in TOMS, respectively, indicating a similar flow frequency distribution in both catchments. The gentle gradient of the Flow Frequency Curve (see Fig. 2) indicates that low and medium Q were responsible for most of the water yield.

The Mediterranean tributaries that flow from the Iberian Massif had drier characteristics than their Pyrenean counterparts. The River Matarranya is the largest of the rivers from that area flowing into the Ribarroja Reservoir. The River Algars joins the Matarranya 22 km before it enters into the reservoir. The headwaters of these two rivers are located in the same mountainous area, thus their hydro-climatic characteristics are very similar. Data reflect the dry character of the study period (2008–2011). Mean water yield during the study period was 16 $hm^3 year^{-1}$ at NMS (Matarranya) and 12 $hm^3 year^{-1}$ at BMS (Algars), both being well below the historical means (i.e. 31 and 20 $hm^3 year^{-1}$, respectively, from 1974 to present) (see Table 1). Mean Q at NMS was 0.5 $m^3 s^{-1}$ (SD=1.9 $m^3 s^{-1}$), while at BMS it was 0.4 $m^3 s^{-1}$ (SD=1.3 $m^3 s^{-1}$). Discharge was especially low during summer months, and in all the years the channel became dry in both sections (i.e. 7 and 23 % of the time at NMS and BMS, respectively). Peak Q at NMS was 50 $m^3 s^{-1}$ (October 2011, $Q_{1.6}$) while at BMS it was 39.5 $m^3 s^{-1}$ (March 2011, $Q_{1.7}$). The interannual variability was remarkable in comparison with the Pyrenean tributaries reaching a CV of 383 % at

NMS and 357 % at BMS. In these Mediterranean rivers, flood flows are responsible for the basin's water yield. Figure 2b shows their flow duration curves where, for instance floods at NMS (from an arbitrary threshold taken as two times the mean flow, i.e. <1 $m^3 s^{-1}$) represent <7 % of the time and are responsible of >60 % of the total water yield, whereas at BMS, floods represent 10 % of the time and are responsible of more than two thirds of the water yield.

The MRFDC exerts a notable impact on the hydrology of the lower River Ebro. Hydrological characteristics of the most representative sections in the lower Ebro are summarised below (i.e. RMS, AMS and TMS; see Fig. 1d for exact locations). The flow pattern was very similar for all these sections downstream of MRFDC. Mean annual runoff during the study period was 9,180 hm^3 in RMS and 8,728 hm^3 in TMS, at both ends of the lower Ebro study reach. Water abstraction (ca. 1,183 $hm^3 year^{-1}$) that takes place through irrigation canals upstream of Xerta (i.e. XMS; see Fig. 1d) was the main reason for the differences between AMS and TMS (Fig. 2c). Mean Q in the monitoring sections range from 291 $m^3 s^{-1}$ (SD=205 $m^3 s^{-1}$) at RMS to 277 $m^3 s^{-1}$ (SD=202 $m^3 s^{-1}$) at TMS. Interannual runoff variability was rather low (73 % at both RMS and TMS), and in the range of the values stated for the upstream Segre-Cinca system. Maximum discharge in all the sections was registered during a *natural* flood (Batalla and Vericat 2009) which occurred in January 2010, when the peak discharge released from the Ribarroja Dam reached 2,028 $m^3 s^{-1}$, a discharge equivalent to a 4-year return period (Q_4), while at TMS the peak discharge attained 1,300 $m^3 s^{-1}$ ($Q_{1.5}$). Figure 2c shows that high flows (i.e. >600 $m^3 s^{-1}$), which represent about 10 % of the time at all three sections, were responsible of about one fourth of the total water yield, with little variation between sections. The percentage of the water yield transported by 50 and 90 % of time for the three sections was also very similar, about 3/4 and 95 % respectively, showing a rather constant flow regime for all the reaches and for the whole study period.

5 Sediment load

5.1 Suspended sediment transport

Suspended sediment concentrations of the Ebro River at SMS showed higher values to those observed in the River Ebro downstream from MRFDC. This fact is closely related with the sediment load provided by the main tributaries upstream from the Mequinenza Reservoir (e.g. Gállego and especially Jalón) and the lower regulation of the river in this reach. The mean SSC for the study period (calculated as the mean of the estimated concentrations) was 56 $mg l^{-1}$.

In the case of the Pyrenean tributaries, the mean observed SSC were generally higher than those in the Iberian tributaries. Mean SSC for the study period in the River Segre (i.e. SEMS) was 23 $mg l^{-1}$ (SD=28 $mg l^{-1}$), lower than the 56 $mg l^{-1}$ (SD=116 $mg l^{-1}$) registered in Cinca (i.e. TOMS). Maximum measured SSC was also higher in TOMS (2,030 $mg l^{-1}$) than in SEMS (1,550 $mg l^{-1}$). Rivers from the Iberian Massif had mean SSC of the order of 10 $mg l^{-1}$ (9 $mg l^{-1}$ for the Algars (i.e. BMS), with a SD=12 and 4 $mg l^{-1}$ for the Matarranya (i.e. NMS) with a SD=10 $mg l^{-1}$). Maximum measured SSC was also higher in BMS with a peak of 630 $mg l^{-1}$, two times the peak registered at NMS (i.e. 310 $mg l^{-1}$). Maximum SSC were reached during the year 2009–2010 but under different flow conditions i.e. in the case of the Matarranya it coincided with the maximum discharge (32 $m^3 s^{-1}$), while in the case of the Algars it occurred during a low magnitude flood (0.75 $m^3 s^{-1}$).

Suspended sediment transport in the lower Ebro is altered by trapping occurring at MRFDC, being one order of magnitude lower than the estimated values upstream from the Mequinenza Dam. Mean SSC remains rather stable for the whole reach (Table 2), although a certain increase can be seen from upstream to downstream sections. As previously reported (e.g. Tena et al. 2012a), this suggests that clearwater released by the dams is progressively recharged with fine sediments from channel erosion and ephemeral tributaries. Mean SSC increases from <5 $mg l^{-1}$ at RMS to almost 10 $mg l^{-1}$ at MEMS, XMS and TMS. Variability of mean SSC between the three-year study period was low for all sections (SD=2 $mg l^{-1}$). In the three upstream sections, maximum SSC was reached during *flushing flows* (Batalla and Vericat 2009), i.e. 214 $mg l^{-1}$ in RMS in May 2010, and 260 and 274 $mg l^{-1}$ in AMS and PAMS in October 2009, respectively. In the most downstream monitoring sections, maximum SSC was influenced by tributary inputs (see Tena et al. 2012a). For instance, in MEMS the maximum value was 845 $mg l^{-1}$ (April 2009) for a low discharge of 350 $m^3 s^{-1}$ but was associated with a sediment pulse from the River Siurana following a storm event. It is worth mentioning that this value is in the same order of magnitude as the maximum SSC observed during a *natural* flood by Vericat and Batalla (2006). In XMS and TMS, maximum SSC (698 and 513 $mg l^{-1}$, respectively) were recorded in October 2009, also during a storm related sediment pulse, in this case from the Canaletes Creek.

5.2 Load frequency

The frequency of the SSL has been examined at the different monitoring sections. Results are presented as load duration curves (see Figs. 2a–c). This method shows the fraction of the total SSL that is transported during a given percentage of time, i.e. duration curves in cumulative percentage of transported sediment. Different patterns are distinguished depending on the hydrological regime of the river and the

Table 2 Suspended sediment data (concentration, SSC; load, SSL; and yield, SSY) for the study period at the monitoring sections in the lower River Ebro and its main tributaries (see Fig. 1d for exact locations and notations)

Area	Section	Year	SSC_{mean} (mgl^{-1})	SSC_{max} (mgl^{-1})	SSC_{min} (mgl^{-1})	SD (mgl^{-1})	Total SSL (10^6t)	SSY (tkm^{2}year^{-1})
Iberian tributaries	BMS	2008–2009	9.7	632.9	0.0	14.4	0.00024	0.7
		2009–2010	6.9	261.7	0.1	7.4	0.00007	0.2
		2010–2011	10.0	510.0	0.4	13.1	0.00053	1.6
		2008–2011	8.9	632.9	0.0	12.1	0.00083 (0.00028[b])	0.9
	NMS	2008–2009	4.5	309.3	0.4	13.0	0.00064	0.6
		2009–2010	3.2	46.0	0.4	2.5	0.00003	0.0
		2010–2011	3.9	280.7	0.7	10.1	0.00075	0.7
		2008–2011	3.8	309.3	0.4	9.6	0.00143 (0.00048[b])	0.5
Pyrenean tributaries	TOMS	2008–2009	80.4	2,033.0	7.5	167.1	0.154	16.0
		2009–2010	50.7	1,701.5	8.8	81.1	0.144	15.0
		2010–2011	35.4	1,434.5	6.7	71.0	0.067	6.9
		2008–2011	55.5	2,033.0	6.7	116.3	0.365 (0.121[b])	12.7
	SEMS	2008–2009	26.6	486.5	6.1	27.9	0,057	4.5
		2009–2010	25.0	1,551.7	7.2	38.0	0,047	3.7
		2010–2011	16.9	222.0	6.1	9.7	0,018	1.4
		2008–2011	22.8	1,551.7	6.1	28.1	0.121 (0.040[b])	3.2
Ebro mainstem[a]	SMS	2008–2009	69.5	510.0	16.5	73.3	1.069	20.9
		2009–2010	55.8	484.8	16.3	48.8	0.621	12.1
		2010–2011	42.5	283.5	9.0	33.0	0.288	5.6
		2008–2011	55.9	510.0	9.0	55.4	1.978 (0.659[b])	12.9
	RMS	2008–2009	5.5	72.4	0.0	4.2	0.060	0.7
		2009–2010	5.4	214.2	1.4	5.7	0.048	0.6
		2010–2011	3.6	206.2	0.2	4.6	0.024	0.3
		2008–2011	4.9	214.2	0.0	4.9	0.131 (0.043[b])	0.5
	AMS	2008–2009	7.4	129.7	2.5	4.5	0.073	0.9
		2009–2010	6.6	260.4	1.7	7.3	0.063	0.8
		2010–2011	4.1	234.1	1.7	6.4	0.030	0.4
		2008–2011	6.0	260.4	1.7	6.3	0.166 (0.055[b])	0.7
	PAMS	2008–2009	7.6	136.9	2.6	4.8	0.076	0.9
		2009–2010	6.7	274.1	2.0	7.7	0.064	0.8
		2010–2011	4.0	246.2	2.0	6.7	0.030	0.4
		2008–2011	6.1	274.1	2.0	6.7	0.170 (0.056[b])	0.7
	MEMS	2008–2009	9.9	845.2	0.0	26.8	0.099	1.2
		2009–2010	7.6	311.0	0.0	8.6	0.073	0.9
		2010–2011	6.3	235.6	0.0	8.7	0.043	0.5
		2008–2011	7.9	845.2	0.0	17.1	0.215 (0.071[b])	0.9
	XMS	2008–2009	10.2	123.6	4.9	5.6	0.089	1.1
		2009–2010	10.3	698.5	2.4	18.3	0.087	1.1
		2010–2011	5.8	152.3	1.2	5.9	0.036	0.5
		2008–2011	8.8	698.5	1.2	11.7	0.212 (0.070[b])	0.9
	TMS	2008–2009	10.3	265.1	1.5	10.7	0.085	1.1
		2009–2010	9.3	512.7	0.1	14.9	0.078	0.9
		2010–2011	5.9	148.5	2.0	5.6	0.035	0.4
		2008–2011	8.5	512.7	0.1	11.2	0.198 (0.066[b])	0.8

SD standard deviation

[a] Sections ordered following the river course

[b] Mean value

relative position of the section within the study area (i.e. degree of regulation). The SSL in the Pyrenean tributaries appears to be relatively constant. Figure 2a indicates that 90 % of the sediment was transported in approximately

75 % of time in the River Cinca (corresponding to Q>35 m^3 s^{-1}), while in the Segre the same proportion was transported in approximately two thirds of the time (for Q>29 m^{3}s^{-1}). Floods and high flows (taken as twice the mean Q) were responsible of 43 (Segre) and 52 % (Cinca) of SSL during the study period. In the case of the Iberian Massif tributaries (see Fig. 2b), 90 % of SSL was transported in 13 % of the time (for Q>0.6 m^{3}s^{-1}) in the River Algars, and in <2 % of the time in the case of the Matarranya (for Q>3.8 m^{3}s^{-1}). In these two rivers, SSL was much more dominated by floods, which may attain 95 % of the annual load (e.g. 2009 and 2011). Overall, curves are steeper for rivers in the drier environments (i.e. Mediterranean basins of the Iberian Massif); there, floods are responsible for transporting a larger portion of the sediment in comparison with their humid counterparts.

Regarding the Ebro mainstem, SMS appears to be the section where SSL is more variable in time. Sediment duration curves (see Fig. 2c) shows that 90 % of SSL was transported in 36 % of the time (Q>174 m^{3}s^{-1}), showing an intermediate character between the Iberian and the Pyrenean catchments. Flood and high flows are responsible of 74 % of the total SSL. Further downstream, the frequency of SSL is altered by MRFDC. Natural variability from tributaries disappears and SSL is more constant in time. Moreover, the relation between SSL and Q tends to be more linear (Tena et al. 2011). The relation between SSL and time shows a similar load duration pattern for all the monitoring sections. The cumulative time required to transport 90 % of the SSL ranges from 64 % in the case of RMS (Q>187 m^{3}s^{-1}) to 72 % in the case of MEMS (Q>176 m^{3}s^{-1}). Note, that this relation is in the range of that observed for the Segre-Cinca system, a fact that suggests that: (a) the two main tributaries still exert a certain influence on the lower Ebro sediment load dynamics and (b) the two systems (Segre-Cinca and Ebro) are subject to a high degree of regulation that is manifested in their respective SSL durations (especially for the Segre and the Ebro). Flood and high flows are responsible of 38 % of the total SSL in the lower Ebro, much lower than those reported for SMS and the Iberian tributaries.

6 The sediment budget of the lower Ebro

The fluvial sediment budget of the lower Ebro basin takes into account the sediment transport estimated upstream from the Mequinenza Reservoir, the main sediment fluxes entering into the Ribarroja Reservoir, and the load observed in the downstream reaches of the river. The main objective is to assess the sediment fluxes (inputs vs. outputs) around the Ribarroja Reservoir, and

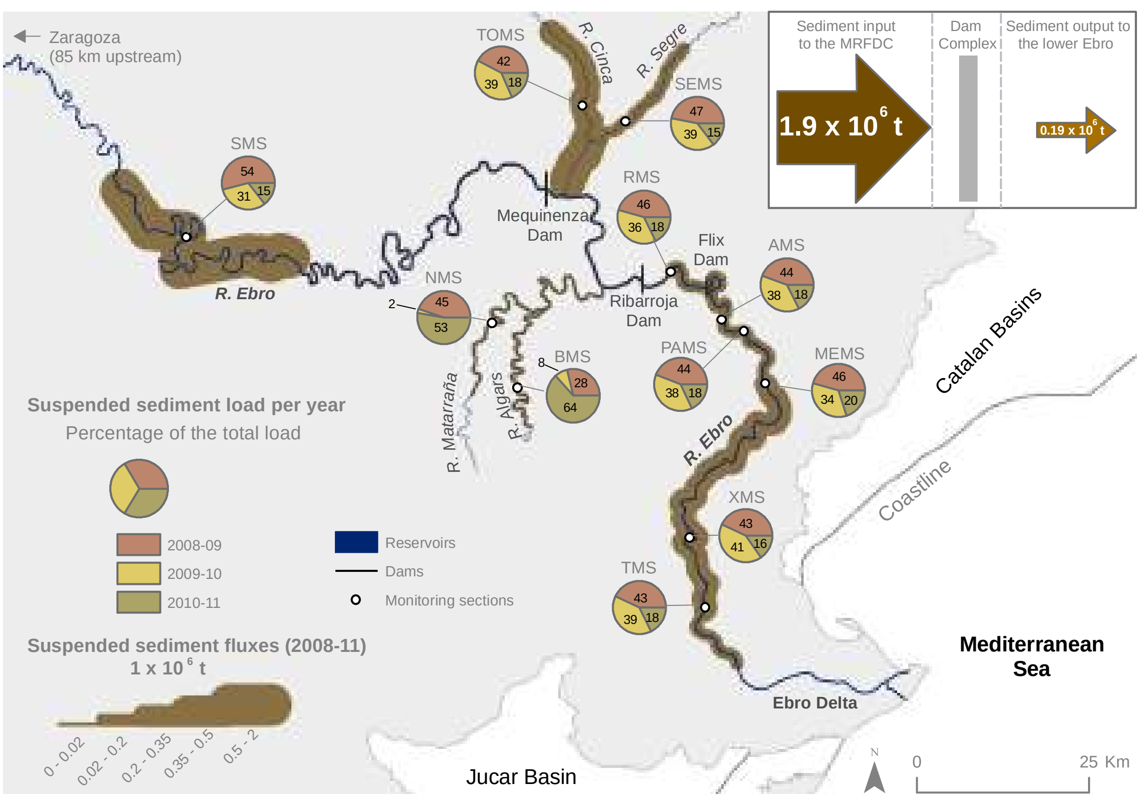

Fig. 3 The sediment budget of the lower River Ebro for the study period 2008–2011. Main sediment fluxes are indicated and scaled, while the annual distribution of the sediment load is shown for each of the monitoring sections. Note that MRFDC in the *inset* indicates the Mequinenza–Ribarroja–Flix Dam Complex. See Fig. 1d for location details

discuss them in light of the hydrology of the tributary basins and the role played by the dams. Figure 3 summarises the sediment budget of the study area and presents the main sediment fluxes for the study period.

6.1 Sediment load upstream from the Mequinenza Reservoir

Water yield and peak Q were similar during our study period and the years previously reported by Vericat and Batalla (2006). Therefore the routed flow duration curves for the period 2008–2011 coupled with the statistically significant relation between Q and SSC obtained in 2003–2004, give us a reliable estimation of SSL at SMS during the study period. For comparison, Vericat and Batalla (2006) calculated a sediment yield of 1×10^6tyear^{-1} for a water yield of 7,263 hm^3, while in our case the sediment yield in 2008–2009 was 1.1×10^6tyear^{-1} for a water yield of 7,384 hm^3. Roura (2004) determined a sediment yield of 0.5×10^6t for years with mean annual water yield at around 5,700 hm^3; this value matches our values for the drier years, i.e. 2009–2010 with a water yield of 6,275 hm^3 and a SSL of 0.6×10^6t of sediment, and 2010–2011 with 4,121 hm^3 of water and 0.3×10^6t of sediment. The SSL estimated for the River Ebro upstream the Mequinenza Reservoir (i.e. SMS) was 2.0×10^6t for the period 2008–2011, yielding a mean annual load of 0.6×10^6t. This result represents a specific sediment yield of around 13 tkm^{-2}year^{-1}; lower than those obtained by Sanz et al. (1999) and Vericat and Batalla (2006) during wetter periods (30 tkm^{-2}year^{-1}) and higher than those during drier years reported by Palanques (1987) of 7 tkm^{-2} year^{-1} and Roura (2004) of 10 tkm^{-2}year^{-1}. The estimated load entering the Mequinenza Reservoir is in the order of magnitude as other large rivers of Western Europe, such as the Garonne and the Rhine, whose yields are 21 and 15 t km^{-2}year^{-1}, respectively (Meybeck and Ragu 1997). Although the site is already affected by a structural sediment deficit due to the upstream reservoirs (for details, see Batalla and Vericat 2011), this section still maintains a certain natural behaviour. This fact is shown by the remarkable interannual variability of SSL that accounts for up to 60 % between the wettest and the driest years. Owing to its size and impounding capacity, water residence time in the Mequinenza Reservoir is high (on average between 1 and 2.5 months according to Prats et al. 2009), thus favouring the settling of most of the sediment load transported by the Ebro. Roura (2004) estimated a trapping efficiency in this reservoir of 95 % during a 2-year study period (1998–2000).

6.2 Sediment load flowing into the Ribarroja Reservoir

The fraction of SSL that passes through the Mequinenza Dam flows directly into the Ribarroja Reservoir. Based in the sediment trapping obtained by Roura (2004) (i.e. 95 %), our estimates indicate a value of ca. 0.1×10^6t for the period 2008–2011. Three kilometres downstream from the Mequinenza Dam, the Ebro receives input from the two main tributaries draining the Pyrenean Range (Segre and Cinca Rivers, see Fig. 1d). The total SSL from these two northern rivers was 0.49×10^6t (ca. one fourth from Segre and three fourths from Cinca during the 3-year study period). Annual SSL were 0.21×10^6t in 2008–2009, 0.19×10^6t in 2009–2010 and 0.08×10^6t in 2010–2011. Specifically, the total SSL at SEMS (River Segre) for the study period was 0.12×10^6t (SD=0.02×10^6t), yielding a mean annual SSL of 0.04×10^6t (see Table 2); in turn, the annual SSL obtained at TOMS (River Cinca) was 0.36×10^6t (SD=0.05×10^6t). As in the case of the water yield, interannual sediment variability is relatively low, with CVs of 39 and 50 %, respectively. The average SSY for the whole study period ranged from 3.2 tkm^{-2}year^{-1} in the case of the Segre River to 12.7 tkm^{-2}year^{-1} in the case of the Cinca River. Although these SSY are remarkable for such large basins, values remain below those reported for other rivers worldwide draining mountain areas (e.g. Dedkov and Mozzherin 1996).

Approximately 28 km downstream from the confluence of the Pyrenean tributaries, the Matarranya River (including its main tributary, the Algars, see Fig. 1d) debouches into the Ribarroja Reservoir. Owing to their humid character, the contribution of the Pyrenean tributaries is much larger when compared with their Iberian Massif counterparts, both in absolute and in relative terms. The total SSL coming from these southern tributaries was 2,260 t for the study period. Annually, it was distributed as 875, 102 and 1,280 t for 2008–2009, 2009–2010 and 2010–2011, respectively. Due to its larger area, the SSY from the Matarranya is bigger than that from the Algars. The total SSL that passed through NMS (River Matarranya) was 1,426 t, yielding a mean annual SSL of 475 t (SD=385 t; see Table 2). This value is higher than the 831 t passing through BMS (River Algars). In both cases, SSL encompasses a strong interannual variability, ranging from 35 (2009–2010) to 751 t (2010–2011) in the case of the Matarranya and from 67 (2009–2010) to 528 t (2010–2011) in the Algars (see Table 2). These values represent CVs of 123 and 84 % for NMS and BMS, respectively. In contrast, SSY (0.85 tkm^{-2}year^{-1}) of the Algars is higher than that in the Matarranya (0.46 tkm^{-2}year^{-1}) and both are lower when compared with other Mediterranean rivers with similar catchment areas (e.g. Inbar 1992; Batalla et al. 2005). These loads are not directly related with the annual water yield whose maximum was recorded in 2008–2009; in contrast, it seems to be related to the largest flood, which took place in the hydrological year 2010–2011 and which was responsible of the 61 (322 t) and 45 % (339 t) of the SSL transported in this year in the two rivers, respectively. The low values observed in these tributaries can be attributed to a combination of factors that will be discussed further.

The total SSL entering the Ribarroja Reservoir was ca. 0.60×10^{6}t for the whole study period; annually, it was 0.27×10^{6}t in 2008–2009, 0.22×10^{6}t in 2009–2010 and almost 0.1×10^{6}t in 2010–2011. Although the size (35 km long and 220 hm^3 of capacity) and the mean residence time (9 days) is smaller than that of the Mequinenza Reservoir, a large amount of the SSL supplied from the tributaries and the mainstem is also trapped in the Ribarroja Reservoir (e.g. Vericat and Batalla (2006) estimated a retention rate of 90 %).

6.3 Sediment load downstream from the Ribarroja Dam

The impact of the MRFDC on the SSL of the lower Ebro is remarkable. Sediment load decreases and becomes more constantly distributed through time. RMS (just downstream of the Ribarroja Reservoir) showed the lowest SSL in the reach, with 0.13×10^{6}t (SD=0.02×10^{6}t, see Table 2 for annual data). This value represents ca. one fifths of the upstream total SSL estimation, i.e. 5 % if we compare it with the upstream load including SMS. Similar percentages of retention were estimated by Avendaño et al. (1997) based on reservoir sedimentation, Sanz et al. (1999) based on infrequent sampling, Vericat and Batalla (2005a) following the method by Brune (1953) and data from two single extraordinary floods and Vericat and Batalla (2006) based on regular frequent sampling.

Sediment load increases as the river flows downstream, with AMS and PAMS yielding a total SSL around 0.17×10^{6}t (SD=0.02×10^{6}t) and MEMS yielding 0.22×10^{6}t (SD=0.03×10^{6}t). Despite the low capacity and small residence time (few hours) of the Flix Reservoir, it still exerts certain sediment retention. Tena et al. (2012b) pointed out that much of the sediment produced between RMS and AMS does not pass through the Flix Dam, but comes from riverbed erosion in the reach downstream from the dam. Further downstream the observed difference between AMS and PAMS (see Fig. 1) is very small, i.e. 4,000 t for the 3-year period. This fact can be explained by the short distance that separates both sections, as well as for the absence of tributaries in the reach between them. The increment of SSL at MEMS is remarkable, i.e. reaching 0.22×10^{6}t, in comparison to the 0.17×10^{6}t registered at PAMS. MEMS is located downstream from the River Siurana (see Fig. 1d), the main tributary of the lower Ebro. Even though the river remains inactive most of the time and water and sediment delivery is rare due to dams and gravel mining, it can contribute significantly during localized rainfall events. For instance, SSC in the River Siurana during a flood in April 2009 reached 1 gl^{-1}, a value that is several orders of magnitude larger than those typically obtained in the Ebro mainstem; that flood together with another one two days later can be taken as the basis to explain the difference in SSL observed between PAMS (and AMS) and MEMS.

Further downstream, SSL stays rather constant until the lowermost sections (i.e. XMS, 0.21×10^{6}t (SD=0.03×10^{6}t) and TMS, 0.19×10^{6}t (SD=0.03×10^{6}t)). Particularly, total SSL transferred from MEMS to XMS was slightly lower over the 3-year term, from 0.22×10^{6}t to 0.21×10^{6}t, respectively. This general trend, however, was not followed in 2009–2010, when SSL at XMS (0.09×10^{6}t) was larger than that at MEMS (0.07×10^{6}t). This downstream increment can be attributed to the sediment supplied from the ephemeral Sec and Canaletes creeks. As in the case of the Siurana, their runoff contribution to the *Q* of the Ebro was negligible; however, during torrential events, their sediment supply may increase notably SSL at XMS (see Tena et al. 2012a). Finally, there is no tributary contribution in the river reach between XMS and TMS explaining the overall stability in the observed SSL (i.e. 0.19×10^{6}t) in the lowermost monitoring section (see Fig. 1d).

Annual SSL were directly related with the observed hydrology (i.e. there is a positive relation between water yield and sediment load), and followed the same pattern in all sections, i.e. higher SSL in 2008–2009 and lower in 2009–2010 and 2010–2011 (see Table 2). Sediment variability amongst years was moderated and almost constant between sections (mean CV between 38 and 43 %). The SSY for the lower Ebro is very low, with an average of around 0.7 tkm^{-2} year^{-1} for all the monitoring sections, as would be expected for such a regulated system. This value is slightly lower than that estimated previously by the authors for a 10-year period for two consecutive sections i.e. PAMS with 1 tkm^{-2}year^{-1} and XMS with 1.3 tkm^{-2}year^{-1} (see Tena et al. 2011, 2012a). The differences between the estimates from this study and recent studies of the lower Ebro (e.g. Vericat and Batalla 2006; Négrel et al. 2007) can be easily attributed to the dry character of the study period (2008–2011). Finally, the SSY of the lower Ebro remains low in comparison with those obtained in similar large impounded rivers (i.e. Rhine, 15 tkm^{-2}year^{-1} (Meybeck and Ragu 1997) and Rhône, 101 tkm^{-2}year^{-1} (Serrat et al. 2001)).

7 Summary and final remarks

The fluvial sediment budget of the lower Ebro has been assessed during a 3-year period by means of detailed monitoring of water and sediment loads at the several inflows and outflow of the Ribarroja Reservoir. Continuous records of *Q* and SSC together with previous data have been used to estimate the various sediment fluxes and the rate of sediment transfer to the downstream reaches. The lower River Ebro is a representative case study of the water and sediment dynamics of a large Mediterranean river regulated by dams. The work represents a complete assessment of the sedimentary status of a river of this nature and culminates a decade of geomorphic research by the RIUS team in this geographical area.

The MRFDC modulates the particular characteristics of both the Pyrenean tributaries (larger volumes of water, more regular runoff and sediment supply) and the Iberian streams (less water volume and runoff continuity and sporadic sediment load). Overall, the dams result in notable reservoir sedimentation and a marked downstream sediment deficit. The sediment budget proves that the MRFDC reduces the sediment delivered to the lower Ebro. However, the main tributaries (i.e. Pyrenean basins) are already influenced by sediment deficit before they get into the Ribarroja Reservoir. This phenomenon is associated with the presence of large reservoirs and the reduction in runoff (hence erosion and sediment yield) due to the afforestation that took place in this areas following land abandonment during the second half of the twentieth century (Gallart and Llorens 2004). Furthermore, Lopez-Moreno et al. (2008), attribute this reduction in runoff to less precipitation and snow accumulation, plus an increase in evapotranspiration.

The total SSL trapped in the MRFDC for the 3-year study period was estimated at 2.3×10^6t (95 % of the sediment provided by the River Ebro upstream Mequinenza Dam and the main tributaries), yielding a mean annual retention of 0.75×10^6t. The monitoring period can be classified as dry, therefore the SSL reaching the MRFDC was presumably very low in comparison with reported long-term values (e.g. Batalla and Vericat 2011). For instance, the total SSL entering the Mequinenza Reservoir in our study period was of the order of 2×10^6t, lower than that reported by Vericat and Batalla (2006) for just a single year (2002–2003). Below dams, SSL increases gradually in the downstream direction. Clearwater released from the Ribarroja and Flix dams (i.e. showing high sediment transport capacity especially during flushing flows, see Batalla and Vericat 2009 for details) scour riverbed and banks enough to increase SSL of the river up to a few hundred thousand tons per year. Previous works (e.g. Vericat and Batalla 2006; Tena et al. 2012b) have demonstrated that erosion processes are not extraordinary and, owing to the large amounts of water released from the dams, SSC remain low (<300 mgl^{-1}), even during flood events. In addition, the sediment budget has revealed that floods are not the only drivers of the sediment dynamics in the lower Ebro. The particular location of the monitoring sections (i.e. some located few kilometres downstream from tributary confluences) has shown that episodic contributions from small tributaries alter the general SSL of the river. Similar phenomena have been reported in other large impounded rivers as the River Green, USA (Schmidt 2007). In the case of the Ebro, Tena et al. (2012a) found that sediment delivery from ephemeral tributaries during torrential events was even larger than the sediment transported during flushing flows (i.e. 5 % of the mean annual load for the period 1998–2008).

Overall, the fluvial sediment budget of the lower Ebro provides key information to understand the sedimentary behaviour of a large river under modified conditions, highlighting the crucial role played by processes, such as reservoir trapping, channel erosion and downstream inputs from ephemeral tributaries. This detailed knowledge should be considered as a basis to design and model strategies for sediment management in the lower Ebro, towards a renaturalization of the river's sedimentary regime. To date, restoration practises are performed in the lower Ebro through regular reservoir releases (i.e. flushing flows, see Batalla and Vericat 2009). These artificial floods have been designed and implemented since 2002 in this part of the river with the objective of controlling macrophyte populations and maintaining a certain degree of channel dynamism. Flushing flows have demonstrated their effectiveness in removing macrophytes (95 % in areas close to the Flix Dam, although removal rate decreases downstream) and their potential to entrain and transport coarse sediment to the lowermost river reaches. In addition, flushing flows have a higher sediment transport capacity than their natural counterparts (Batalla and Vericat 2009; Tena et al. 2011, 2012b); a fact that combined with other restoration measures such as sediment injections may benefit the riverine ecosystem, maximizing sediment delivery to distal river reaches.

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