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Suspended sediment load at the lowermost Ebro River (Catalonia, Spain)

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ABSTRACT

Several attempts to estimate the suspended load and the sediment deficit caused by the reservoirs have been carried out in the lower Ebro River. However, existing data are scarce, scattered along time and space, and obtained under different hydrological conditions and methods. This study estimate the presently suspended sediment load of the lowermost Ebro River, using field data collected during three consecutive years at different verticals of a cross-section and covering a large range of discharges. In addition, the daily suspended load for the last 30 years has been reconstructed and validated. The suspended load for the period 2007–2010 has been estimated at 84,000 t/y (±9800 t) while 99,500 t/y (±18,000 t) accounted for 1981–2010 period. Approximately, 80% of the total suspended load (period 2007–2010) has been transferred as inorganic load. A significant seasonal variability in the total (organic and inorganic) suspended load is observed. Therefore, two distinct cycling phases in the suspended load production and transfer has been inferred: an initial phase in which the sediment was prepared into the basin followed by a second phase in which most of the load was transferred downstream. These two phases are governed by the relative temporal location of the natural floods and the river regulation from the reservoirs. Nowadays, less than 1% of suspended load is transferred compared to pre-dams construction. The current levels of suspended load are very low and not enough to supply the material needed to maintain the delta elevation and avoid coastal retreat. The sustainability of the lower Ebro River and its delta could only be guaranteed by the implementation of a new reservoir management concept with the allocation of an appropriate liquid and solid flow regime.

1. Introduction

Under natural conditions, rivers tend to maintain their morphology in a dynamic equilibrium where the amount of sediment exported in a section is similar to that comes from upstream (Williams and Wolman, 1984). From this point of view, the sediment transport in a basin is continuous, being ultimately responsible for the balance between the fluvial and marine processes in delta and coastal areas. However, the transfer of sediment transported from the mainland towards the sea has been severely modified by human activities, mainly as water demand has been growing and fresh water has becoming an increasingly scarce resource. As a consequence, dam construction has been strongly developed.

The construction of dams and reservoir projects produces a number of social benefits. But, in producing these benefits, dams also alter the natural balance of sediment flow in rivers by impounding sediment within and upstream of the reservoir and discharging clean water downstream (Morris and Fan, 2000). For instance, more than 40% of the global river discharge is intercepted by at least 42,000 large reservoirs (≥0.5 km^3 maximum reservoir storage capacity) (Morris and Fan, 2000); and nearly 600 km^3 of reservoir storage is being lost through sedimentation at an annual rate of 1% of the storage volume capacity (the equivalent to ~30 km^3/y) (White, 2001). In its turn, the sediment storage in reservoirs is reducing land–ocean sediment transfer by about 10 Gt/y, equivalent to a reduction of between 33 and 40% of the presently land–ocean sediment flux (Walling, 2006). In consequence, the sediment exported to the sea is drastically reduced. For instance, in the Mediterranean basin, the potential sediment discharged into the sea has dropped over 50% since 1950 (Poulos and Collins, 2002). This reduction, mainly associated with the retention of sediment in reservoirs, leads the disruption of the sediment transport continuity. A clear example is the case of the Colorado River where the

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suspended sediment load severely decreased from 159 × 10^6 t/y to 0.1 × 10^6 t/y after the Hoover dam construction (Meade and Parker, 1985). Under these conditions, the morphological system is dramatically altered and the balance between fluvial sediment input and coastal erosion is altered.

In recent years, the recovery of water and sediment fluxes through an improvement of river and reservoir management is a topic of increasing concern (Rovira et al., 2014). Environmental flows need to incorporate specific requirements for sediment transport in order to avoid the loss of geomorphic functionality of rivers and coastal areas (Ibánez and Prat, 2003). However, sediment data are often scarce, scattered in time and space and obtained under different methods: such is the case of the lower Ebro River.

Since the 1960s, the sediment transport of the lower Ebro River is being altered by the reservoirs of Mequinensa and Riba-roja. As a result, the lower Ebro River and its delta are facing a severe sediment deficit leading to a progressive change of the river channel morphology and sediment transport dynamics (Guillén and Palanques, 1992; Tena et al., 2012), a degradation of the fluvio-deltaic system (Ibáñez et al., 2012a), and a dramatic reduction of fluvial sediment inputs to the delta (Jiménez and Sánchez-Arcilla, 1993). In the long-term, a significant elevation loss of the delta plain due to subsidence and sea level rise is expected, with the prediction that 45% of the emerged delta will be under mean sea level at the end of this century (Ibáñez et al., 2010). In light of this situation, a new water and sediment plan is being developed to achieve sustainable management of the Ebro River and its delta (Rovira and Ibáñez, 2007). This requires the estimation of the past and currently suspended load transferred at the lowermost reaches of the Ebro in order to evaluate the sediment deficit and the required restoration from the reservoirs. However, the existing sediment data are not continuous in space and time and were obtained under different hydrological conditions and methods (Table 1). For example, Roura et al. (2008) collected the samples by means of one automatic sampler placed at the exit of the Riba-roja reservoir. Vericat and Batalla (2006) took the samples by means of a depth-integrating US D-74 sampler in a single column in Móra d'Ebre (located 22 km downstream of the reservoirs). Tena et al. (2012) used water samples obtained during 6 years in Móra d'Ebre by means of a US D-74 sampler to calibrate and complement the turbidity data recorded in a section 16 km upstream of Móra d'Ebre. Négrel et al. (2007) used water samples collected on a monthly basis by the Confederación Hidrográfica del Ebro (CHE) in Tortosa (69 km downstream of the reservoirs); and Guillén and Palanques (1992) obtained water samples in Amposta (in the estuarine zone; 84 km downstream) by means of a water pump. Consequently, comparison is not always reliable.

The suspended load of the lowermost Ebro River has been computed by means of a new set of field sediment samples in order to: 1) evaluate the current suspended load just upstream of the delta (estuary); 2) understand the present organic and inorganic suspended load dynamics and, 3) reconstruct the daily suspended load concentration (SLC) over the last 30 years (from 1981 to 2010). Compared to previous studies, this is the first time that organic and inorganic matters are differentiated. In addition, the physical interpretation of the rating curves between organic and inorganic suspended load and discharge has been performed. Rating curves have been constructed by means of samples collected across the whole river channel section, and the model validated by using existing previous data. This takes into account the spatial variability of the SLC across-section for the computation of the sediment transport, allowing determination of the suspended load from 1981 to the present.

2. Study area

The Ebro river basin (85,530 km^2) is located in the northeast Iberian Peninsula (Fig. 1). It covers the south-facing slopes of the Cantabrian Range and the Pyrenees (in the northern part of the basin), and the north-facing slopes of the Iberian Massif in its southern part. The basin can be divided into four main climatic areas (Batalla et al., 2004): the Atlantic headwaters, with average annual precipitation of about 900 mm, the west-central Pyrenees (about 950 mm), the eastern Pyrenees (about 800 mm), and the southern Mediterranean zone (about 500 mm). Consequently, precipitation varies greatly across the basin due to its topographic and climatologic diversity. Although precipitation shows some degree of variability between years and regions, there is no statistical evidence that rainfall has decreased during the 20th century in any of the regions of the Ebro basin (García, 2000). Mean annual discharge for the period 1913–2010 in Tortosa, located 40 km upstream of the river mouth, is 425 m^3/s giving an average annual water yield of 13,403 hm^3. Runoff varies substantially from year to year, but there has been a significant decrease in discharge along the last century due to increasing water uses in the basin and the river regulation from reservoirs (Gallart and Llorens, 2004).

Nowadays, the impoundment capacity of the approximately 200 dams scattered around the Ebro basin is equivalent to 57% of the mean annual water yield (Batalla et al., 2004). This is a much higher rate of impoundment than that typically encountered in more humid regions and for catchments of similar size (i.e. 5–18% in the river Rhine, Elbe and Wesser; Vericat and Batalla, 2005). Virtually all dams were built during the twentieth

Table 1
Results of the main studies on suspended load carried out in the lower Ebro River after the construction of the Mequinensa-Riba-Roja dam system.

Source	Site	Study period	No samples	Q[a] (m^3/s)	RSLC[b] (mg/l)	MSLC[c] (mg/l)	MSLY[d] (10^{-3} t/y)
Roura et al. (2008)	Riba-Roja	1997–1999	254	180–2100	2–1251	19	370
Vericat and Batalla (2006)	Móra d'Ebre	2002–2004	269	460–2440	3–550	32	270
Tena et al. (2011)	Móra d'Ebre	1998–2008 (2002–2008[e])	452	127–2160	1–240	9	92
Tena et al. (2012)	Xerta	1998–2008	100	53–2479	1.6–274	13	115
Muñoz (1990)	Tortosa	1986–1987	19	50–675	7–25	13	130
Négrel et al. (2007)	Tortosa	1987–2004	274	53–1140	1–107	9	99
Present study	Tortosa	1981–2010	448	98–2025	2–104	13	99
		(2007–2010[f])					84
Guillén and Palanques (1992)	Amposta	1988–1990	No data[g]	110–675	10–21	15	120

[a] Q = Range of sampled discharges.
[b] RSLC = Range of recorded suspended load concentrations (mg/l).
[c] MSLC = Mean suspended load concentration.
[d] MSLY = Mean annual suspended load yield.
[e] Sampling period.
[f] Sampling period.
[g] During the 2 year study period only 7 field campaigns were carried out.

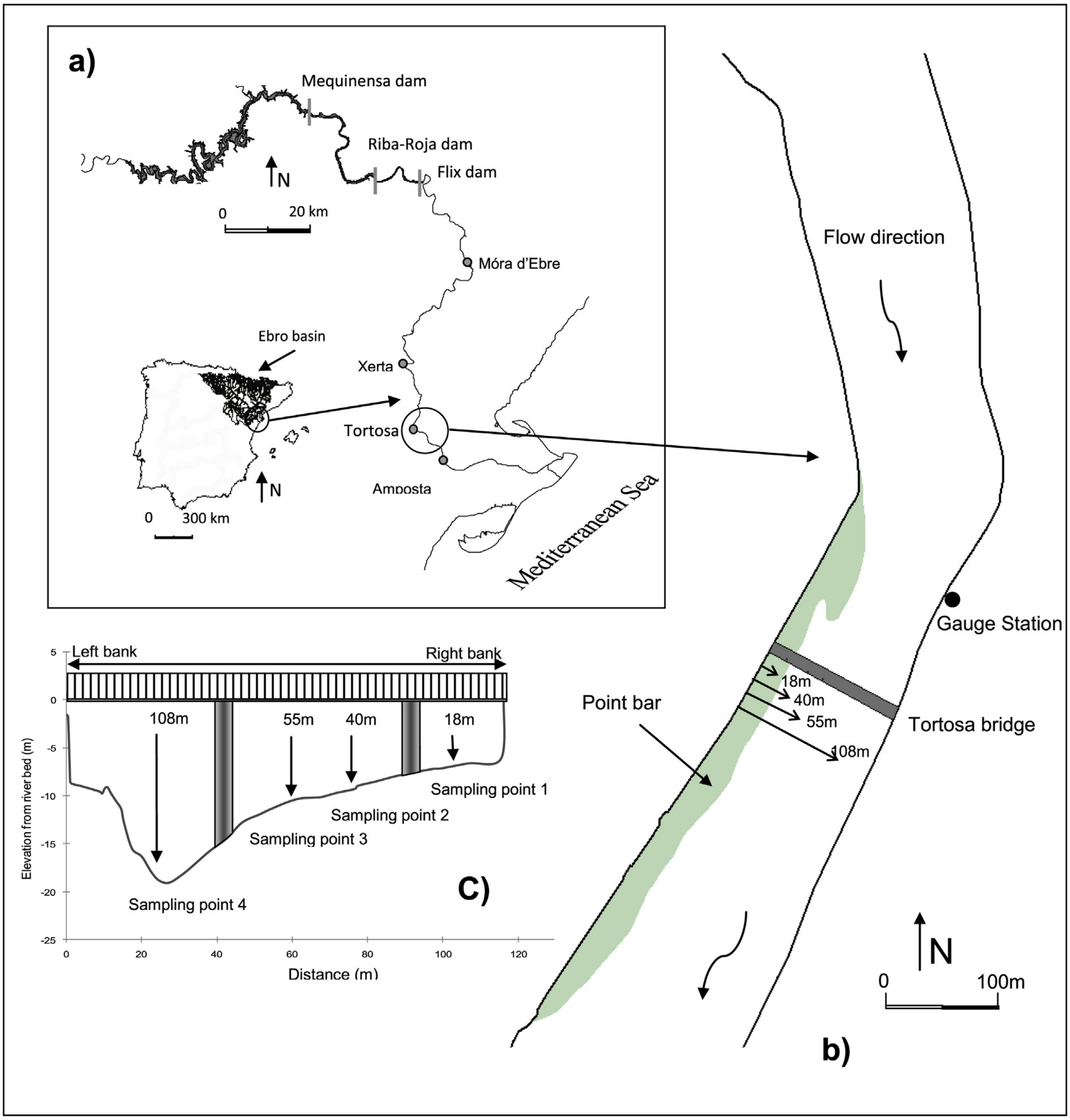

Fig. 1. Location of the study section in the Ebro river basin (a and b) and sampling points in the study channel cross-section (c) in Tortosa.

century, especially in the period 1950–1975 where 67% of the total storage capacity was constructed. The largest system of dams formed by the Mequinensa and Riba-Roja reservoirs is located approximately 110 km from the river mouth (Fig. 1). The main purpose of the dam system is hydropower production. Downstream reservoirs water and sediment inputs from tributaries are not significant, except during local heavy rain events (Tena et al., 2012). After dam construction, frequent floods (i.e. from 2 to 25 years return period) have been reduced by 25% on average (Batalla et al., 2004) whereas reduced and regulated water flows have caused an increase of the saline wedge in the estuary (Guillén and Palanques, 1992). The coastal morphodynamics of the delta is now largely dominated by wave action, so there is a general trend of coastline reshaping by processes of coastal erosion, transport, and redistribution (Jiménez and Sánchez-Arcilla, 1993).

The suspended load transport has been computed in Tortosa (drainage area 83,093 km^2), just upstream of the Ebro delta (Fig. 1). There, the river exhibits a well-defined single-thread channel with a mean width of 130 m and a mean channel slope of 0.05%. The riverbed is mainly composed of unconsolidated coarse and medium gravel with a mean bulk particle size (D_{50}) of 18 mm. For the period 1968–2008, bank-full discharge is estimated at ≈ 1100 m^3/s (based on 1.5 year return period; Batalla et al., 2004).

3. Material and methods

3.1. Field measurements

The sampling programme was designed according to flow conditions, being divided into regular discharges (<600 m^3/s) and flood discharges (>600 m^3/s). This value (600 m^3/s) was chosen because it was defined as the critical discharge for the entrainment of the riverbed particles. During regular discharges suspended load samples were collected at monthly bases, though occasionally the frequency was increased in order to obtain the maximum number of sampled flows while during flood discharges sampling was conducted intensively. During regular discharges, two successive, sequential measurements per vertical (sampling point), were carried out in three/four columns. During flood events, the same procedure was followed, but in this case between 3 and 5 traverses (depending on water stage) were performed in order to account for temporal variations. Sampling was always made from the right-bank to the left-bank. The total sampling duration per day ranged from 2 to 3 h depending on the number of traverses and the flow conditions. The sampling interval from one vertical to another vertical ranged from 15 to 30 min and from 2 to 4 min between two consecutive samples taken at the same point. During the first 3 days the sampling was carried out successively, with decreasing sampling frequency in the following days. This is because maximum variations of hydraulic parameters (i.e. flow velocity, depth and width of the channel) were observed during the first flood stages.

Samples were obtained by means of a 29 kg cable-suspended depth-integrating US D-74. Sampling points were placed avoiding the potential effects of the bridge located in the study section, as follows (Fig. 1): 18 m (Sampling Point 1), 40 m (Sampling Point 2), 55 m (Sampling Point 3) and 108 m (Sampling Point 4) from the right bank. For discharges above 1200 m^3/s, sampling point 4 (left-bank) was not sampled because of security reasons (mean flow velocity above 2.5 m/s for a discharge of 770 m^3/s and the presence of flotsam (debris wood or macrophytes)). In general terms, no significant water discharge variations were observed during each sampling day. In total, 448 depth-integrated water and suspended load samples were collected during the three-year sampling period (2007–2010). 0.75 L of water was collected in every sample. Suspended load was considered as all particles transported in suspension through the water column above 7.6 cm from the riverbed. This limit was marked by the height of the sampler as Emmett (1979) established from his work in the Oak Creek (Oregon, USA). Further details of sampling procedures are described in Rovira et al. (2012).

Samples were filtered between 24 and 48 h after its collection using 45 μm cellulose filters. Once filters were dried (at room temperature) and weighed total SLC (in mg/l) was computed from the differences in filter weight (pre and post filtering). In addition, filters were burned at 450 °C during 4 h in order to estimate the organic matter content (ASTM, 1997).

3.2. Computation of hydro-morphological variables

Hourly water discharge records were used to perform the hydrological calculations. Water discharge was obtained from the gauging station of Tortosa, located 130 m upstream of the cross-section (Fig. 1). Flood events and regular flows were differentiated. A “flood” event was determined by its shape following Tena et al. (2011). Hence, a “flood” had to show a certain similarity to what should be typically a natural flood hydrograph (i.e., steep rising limb and a clear falling limb); in contrast with frequent releases from dams that normally do not follow any hydrological pattern. Differences between flood types were analysed by means of the application of the Flashiness Index (*FI*) (Batalla and Vericat, 2009). This index measures the rate of discharge change per unit time and can be considered as a proxy of the rate of energy expenditure in the channel.

Suspended load for the period 2007–2010 was computed by means of two different methods, both suggested by Walling (1984): the Load Rating Method (*LRM*) and the Flow Duration Curve method (*FDC*). The *LRM* states that statistically significant relationships between flow discharge (*Q*) and SLC may be used to estimate the suspended load during periods or discharges for which samples are not available. The *FDC* is based on the *Q-SLC* rating relationships that are applied to the flow duration curve produced from a high frequency discharge record. The yield for a particular duration increment is calculated as the product of the sediment discharge and its duration. Differences between methods were compared by means of a bias notation (ε) expressed as percentage (Walling, 1977).

The efficiency of the different rating curve models in estimating time series of suspended loads was evaluated using the model efficiency criterion ($E\text{-}R^2$) as defined by Nash and Sutcliffe (1970). The $E\text{-}R^2$ criterion determines the efficiency of the model in comparison with the averaged value. It shows whether the applied model provides better estimations than the application of the averaged value (Asselman, 2000). In addition, the mean error (difference between measured and predicted values) for each of the regressions was assessed and expressed as a percentage (Horowitz, 2003). The physical interpretation of the rating curves was carried out by means of the analysis of the coefficients “*a*” (interception) and “*b*” (slope) in the linear regression fitted in the log-transformed values for the total samples collected across the study section.

Effective discharge (for suspended organic and inorganic load) was calculated following the five-step process proposed by Crowder and Knapp (2005). The initial number of intervals was 25, progressively reduced to 14 to meet the standards of this method. For simplicity, the representative discharge of each class was considered to be the midpoint of the corresponding interval. The effective discharge value was identified as the interval that transports the largest amount of sediment.

3.3. Reconstruction of the 1981–2010 suspended load

Fig. 2 plots the SLC and the associated water discharge of the samples collected at-a-monthly bases by the CHE in Tortosa. The data set covers the 1981–2004 period (no subsequent data) and is almost continuous except for the years 1984–85, 1992–93, and 1998–99. The data set, composed by 274 data of SLC, is available in the CHE Web site (http://www.chebro.es).

The reconstruction of the 1981–2010 suspended load was carried out by using the Q-SLC relationship constructed from samples collected during the period 2007–2010 in Tortosa (Fig. 3). For that purpose the mean SLC (in mg/l) for each sampling day was used without discerning between organic and inorganic load and combining all verticals to obtain a single average. Therefore, a source of error in the estimates of SLC might be introduced for discharges >1000 m^3/s because the asymmetrical river plan geometry and the differential behaviour of the SLC under these hydraulic conditions (Rovira et al., 2012). The obtained suspended load (in t/y) allowed the comparison with previous studies carried out in the lower Ebro River (i.e. Guillén and Palanques, 1992; Négrel et al., 2007). In addition, the capacity of prediction (validation) of the Q-SLC regression model was assessed. For that purpose, the water discharges associated to the SLC of the CHE data set were used to predict the SLC values by means of the Q-SLC regression model 2007–2010. Then, the predicted values, obtained by the Q-SLC regression model 2007–2010, were compared to the observed ones of the 1981–2004 CHE data set. The mean error (difference between the observed values of the CHE and predicted values estimated from the Q-SLC regression model 2007–2010) was computed for 100 m^3/s intervals and expressed as percentages (Horowitz, 2003).

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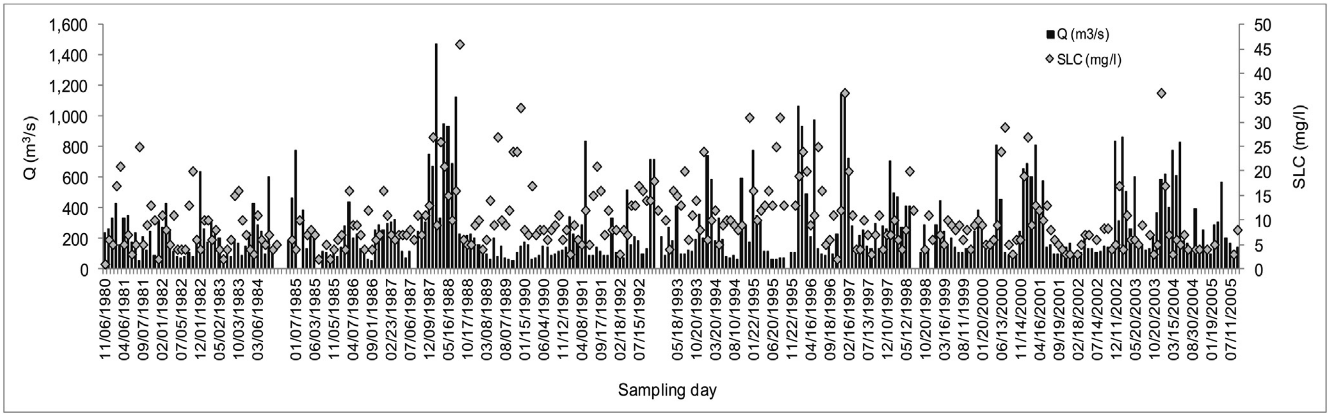

Fig. 2. SLC and Q values of the samples collected at-a-monthly basis by CHE for 1981–2004 in Tortosa.

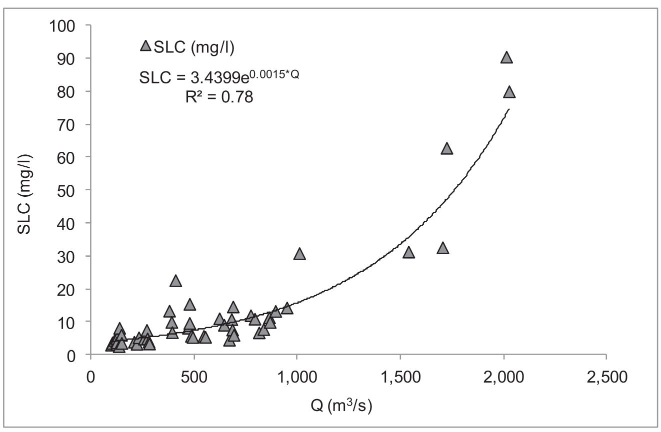

Fig. 3. SLC and Q rating curve for the study cross-section constructed by the samples collected for 2007–2010.

Once the model was validated, the Q-SLC regression model 2007–2010 was used to predict the SLC for each mean daily discharge of the 1981–2007 period, as well as to calculate the total suspended load transferred annually. Finally, a trend analysis of the reconstructed suspended load and the water yield was carried out by application of Spearman's Rho (r_s) and Kendall's-Tau b ($r_{k\text{-}s}$) tests (Spearman, 1904; Kendall, 1938).

4. Results and discussion

4.1. Suspended load relationships

For the period 2007–2010, the mean SLC was 12.9 mg/l ($^{+}$20.8 mg/l (SD)), with a maximum of 90.5 mg/l and a minimum of 2.6 mg/l. This value is the same as reported by Tena et al. (2012) in Xerta, located 14.5 km upstream of our study section, (13 mg/l) and similar to estimates by Guillén and Palanques (1992) in Amposta (15 mg/l) (Fig. 1), but higher than the value obtained in Tortosa (9 mg/l) by Négrel et al. (2007) for 1981–2004. Nevertheless, data analysed by Négrel et al. (2007) correspond to discharges ranging from 53 to 1140 m^3/s, and no data for largest floods are available. Consequently, this value could be slightly underestimated.

Fig. 4 illustrates the relationship between discharge and suspended organic (SOLC) and inorganic (SILC) load concentrations obtained during 2007–2010. The observed scatter in rating relationships is mainly attributed to the exhaustion of the suspended load available in the channel, as well as to the differences in sediment availability at the beginning and end of the floods. The regression coefficients of the fitted curves in the log transformed data are given in Table 2. The evaluation of the E-R^2 factors showed that the model efficiency did not increased when the correction factor was applied. Consequently, the best rating curve model was obtained by least squares regression on log-transformed data without applying the correction factor.

Table 2
Equation coefficients and statistics of the discharge versus inorganic and organic suspended load concentration rating curves developed for the lowermost Ebro River (Tortosa gauging station) for the period 2007–10.

	Interception coefficient	Slope coefficient	Slope standard deviation	Correlation coefficient	Coefficient of determination	Freedom degrees	Mean error (%)	E-R^2 [a]	E-R^2_{SFC} [b]
Inorganic load	−1.7057	0.9544	0.008	0.84	0.70	51	13.9	0.70	0.60
Organic load	−0.4202	0.2581	0.064	0.50	0.25	51	7.8	0.25	0.23
Total suspended load	−1.1301	0.7829	0.081	0.81	0.65	51	11.6	0.65	0.52

[a] Model efficiency criterion obtained in the regression on logarithmic transformed data.
[b] Model efficiency criterion obtained in the regression on logarithmic transformed data in combination with the correction factor.

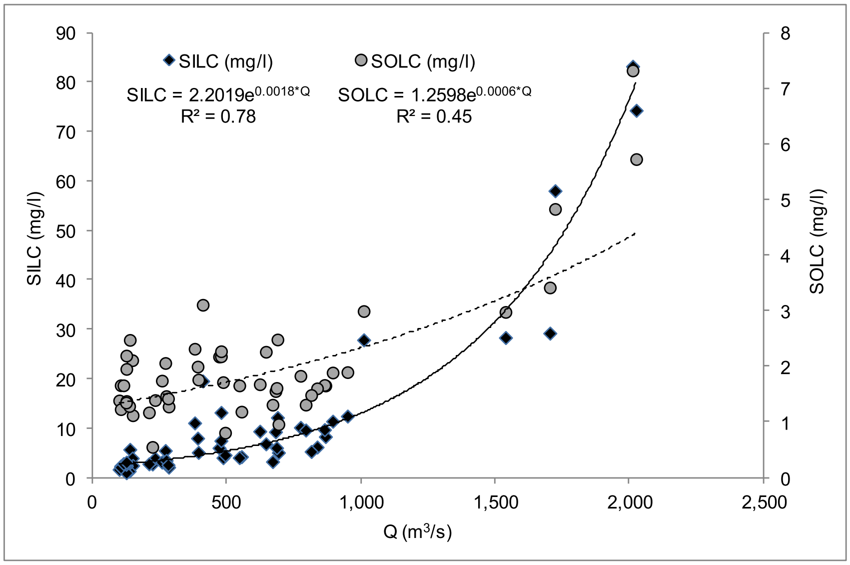

Fig. 4. Seasonal water yield in the lowermost reaches of the Ebro basin for 2007–10.

The steepness of the fitted inorganic load rating curve was relatively high (slope-value> 0.75), being indicative of a strong increase in erosive power and sediment transport capacity when discharge rises. Sediment transport becomes more dependent on high discharges (i.e. flood events) as an important factor controlling sediment yield (Syrén, 1990). In contrast, the relatively low value of the interception-parameter is indicative of the low soil erosion or poor sediment sources available. This reflects the effect of progressive exhaustion (and deficit) of sediment downstream of the reservoirs, as shown by Tena et al. (2012). These authors suggest that the source of fine sediments could primarily be attributed to erosion in the river bed (i.e. bed incision) and bank erosion.

Concerning the organic load rating curve, the relative low value of the interception and slope parameters of the regression line (Table 2) indicate that the organic load transference is much controlled by supply rather than transport capacity. This phenomenon is partially explained because organic matter as a component of the suspended load is only one-third the bulk density of the inorganic matter, and has a higher surface-to-volume ratio (Sedell et al., 1978). Consequently, organic particles stay in suspension longer than inorganic particles, and so once entrained in the water column these tend to remain suspended for a long time (Madej, 2005).

The best regression model that explains the relationship between Q and SLC (Fig. 3) in the Tortosa station is obtained by fitting an exponential function based on a nonlinear least squares regression:

$$SLC = 3.4399 * e^{(0.0015*Q)} \quad R^2 = 0.78 \quad N = 52$$

where SLC is the predicted suspended load concentration (in mg/l) for a given discharge (Q, in m^3/s).

The regression model (used for the reconstruction of the suspended load for the period 1981–2007) shows a good adjustment between the observed and predicted values (estimated mean error 18%); with a low under-estimation for discharges <600 m^3/s (mean error 26%) but slight over-estimation for discharges > 600 m^3/s (mean error 3%).

4.2. *Water fluxes for 2007–2010*

For the sampling period 2007–2010 the mean water yield was estimated at 8986 h m^3/y, very close to the 1981–2010 average (9120 h m^3/y). As well, the flow frequency curve and the number, magnitude and frequency of the floods recorded during 2007–2010 were also very similar to those obtained for the 1981–2010 period. Accordingly, the sampling period was classified as average in hydrological terms. Annually (October to September) the water yield was 7356 h m^3 in 2007–08; 9861 h m^3 in 2008–09 and, 9743 h m^3 in 2009–10. The mean water discharge was 284 m^3/s, giving a mean specific water yield value of 0.003 $m^3/s/km^2$. The spring season (from April to June) contributed to 37% of the total annual water yield, followed by winter (from January to March), which supplied 33%. Autumn (October to December) and summer (July to September) were the driest seasons, with a contribution of 17% and 13%, respectively (Fig. 5). The monthly flow distribution was characterized by two well differentiated phases: a wet period from January to June followed by a dry period from July to December. Significant differences between years were observed. In particular, 2007–08 was a dry year, with an unusual seasonal pattern (compared to the regime of 1981–2010) showing a high homogenization of the mean monthly flow (especially from October to March) and a concentration of the runoff in a short time (April–June) (Fig. 5). In contrast, the period 2008–10 showed the typical seasonal pattern of the 1981–2010 period, with a progressive increase of water flow from October to February, gradually falling from March to August, when the minimum discharge was reached.

During this sampling period (2007–2010) 10 flood events were recorded (Table 3): six events classified as “artificial floods” (i.e. floods generated from the reservoirs to reduce the macrophyte cover; Ibáñez et al., 2012b), and four floods (so-called “natural floods”) resulting from rainfall and snowmelt. Floods accounted for approximately 20% of the total water runoff. Significant differences

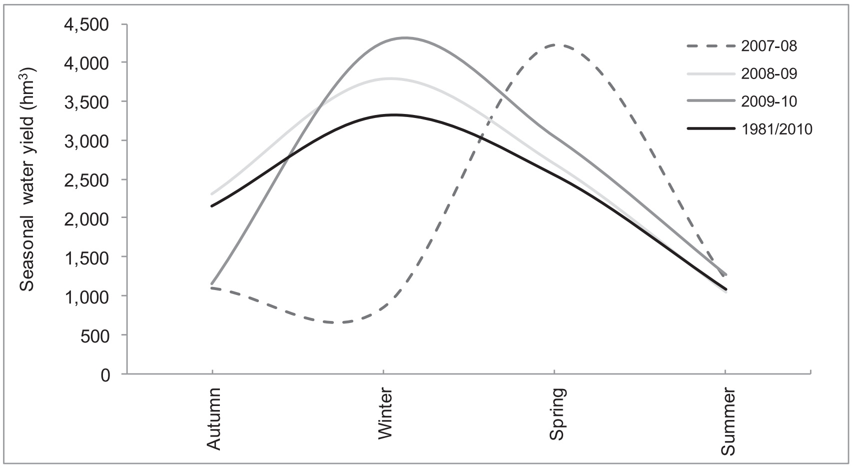

Fig. 5. Suspended organic (SOLC) and inorganic (SILC) load concentration and discharge (Q) rating curves for the study cross-section.

between artificial and natural floods were found (Table 2). Although the first group only represented 1% of total annual water runoff, the natural floods contributed almost 20%. In addition, greatest Flashiness Index values (*FI*) were encountered for artificial floods, indicating a higher steepness of the rising and falling limb of the hydrograph as result of the reservoir management procedures and flood duration. The mean *FI* value for natural floods ($FI = 16$ m^3/s/h) was almost 5 times lower than for artificial ones ($FI = 78$ m^3/s/h). Similar values were obtained by Tena et al. (2011) in a cross-section located 47 km upstream.

Table 3
Principal features of the floods recorded in the lowermost Ebro River during the period (2007–2010). Bold type rows indicate natural floods.

Day	N. Hours	Q peak	Q mean	SD	N. Peaks	FI rising	FI falling
8/11/07	20	848	521.9	236.7	1	91.4	50.1
15/05/08	20	908	600.8	223.2	1	88.3	44.5
26/05/08	**343**	**2052**	**1468.1**	**385.5**	**1**	**28.4**	**4.9**
2/12/08	27	757	440.1	178.2	1	55.4	28.7
27/01/09	**611**	**1088**	**862.2**	**131.4**	**3**	**12.1**	**15.0**
						1.5	**5.6**
						13.9	**7.2**
18/05/09	26	929	670.7	154.0	1	58.4	24.7
21/10/09	31	822	342.6	261.5	1	97.9	31.2
15/01/10	**146**	**1341**	**988.5**	**262.5**	**1**	**30.3**	**9.7**
2/03/10	**191**	**898**	**801.4**	**91.8**	**1**	**6.9**	**5.9**
20/05/10	29	930	618.3	195.2	1	57.3	28.5

4.3. Suspended load fluxes for 2007–2010

Total suspended load transported during the 2007–2010 period was estimated at 252,416 t (±6171 t) (as a mean value of both methods), giving a mean annual value of 84,139 t/y (±4796 t) which represents a mean specific annual yield of 1.01 t/km^2/y (or 9.36 g/m^3). The bias notation (ε) yielded a deviation of 5.9% between the two methods. This sediment load is more than two orders of magnitude lower than the estimated for the lower Ebro River before dam construction (approximately 20–30 $\times$ 10^6 t/y or 241–361 t/km^2/y; Ibáñez et al., 1996). It is at least one order of magnitude lower than for some large rivers of western Europe (i.e. Loire River 8 t/km^2/y and Seine River 9 t/km^2/y), and two orders of magnitude lower than the values (100–200 t/km^2/yr) suggested by Walling and Webb (1996) for Mediterranean basins of the Iberian Peninsula, or the values (200–4000 t/km^2/yr) reported by Lyovich et al. (1991) for rivers in the Northern and Southern Mediterranean region.

Approximately 80% of the total suspended load was transferred as inorganic load, while the remaining 20% was transported as organic load. Thus, the organic matter plays a minor but not insignificant role in the suspended load of the lower Ebro River. A similar proportion was reported by Madej (2005) in the Caspar Creek and the Prairie Creek (USA), but much lower (almost one half) was obtained by Hasholt and Madeyski (1998) for a river basin in Denmark. Nevertheless, under the present conditions the percent of organic load in the lower Ebro River is much higher than expected because of the severe sediment deficit. At annual bases the total suspended load was estimated at 108,261 t (±6171 t) in 2007–08 (1.30 t/km^2/y or 14.7 g/m^3), 72,304 t (±4121 t) in 2008–09 (0.87 t/km^2/y or 7.3 g/m^3), and 71,852 t (±4096 t) in 2009–10 (0.86 t/km^2/y or 7.4 g/m^3) (Fig. 6). The organic load represented 23% of the total load for the period 2008–10, whereas this value fell to 13% for the year 2007–08.

At seasonal scale, SLC described a clockwise loop (Fig. 7a) indicating the progressive exhaustion of suspended load with the succession of the seasons, similar to that described by Asselman (1999) in the Rhine River (Germany), Hudson (2003) in the Panuco River (Mexico), and Rovira and Batalla (2006) in the Tordera River (Spain). Accordingly, the transfer of the suspended load progressively increased from autumn to winter (or spring), to dramatically fall in summer. This behaviour was observed for all the analysed years as well as at monthly scale, where data of Q-SLC described a figure-eight shape (Fig. 7b). As a result, two distinct cycling phases in the suspended load production and transfer were inferred: a first phase in which the suspended load was prepared into the basin (summer and autumn) followed by a second phase in which most of the load was transferred downstream (winter and spring). These two phases were governed by the relative temporal location of the natural floods and the river regulation from the reservoirs. The three analysed years exemplify this pattern. The 2007–08 year was preceded by three years of low flows that allowed the delivery of fine sediment into the river channel. The water energy was concentrated in a very short period of time (May–June), when a large natural flood (return period equal to 5 years) was recorded. As a result, the fine sediment stored into the channel was transferred downstream, yielding the highest annual suspended load but the lowest water yield. In contrast, during the two successive years, low net storage of fine sediment occurred because the water energy was much gradually distributed

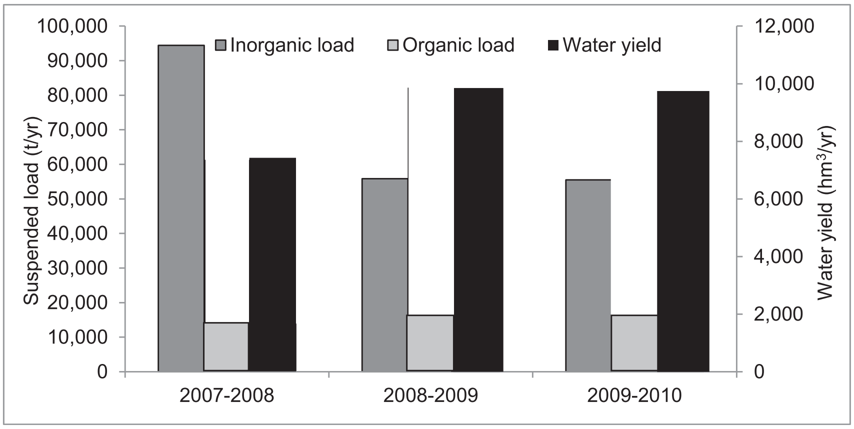

Fig. 6. Annual water and suspended organic and inorganic fluxes computed for 2007–10 in the lower Ebro River before entering the delta.

throughout the year. During these two years the water yield was higher (roughly 25% higher) than in 2007–08, but the total suspended load was 50% lower.

Altogether, natural floods were responsible of 49.7% of the total suspended load transferred to the estuary. This value is higher than the one obtained by Tena et al. (2012) in a section located 14.5 km upstream, where natural floods accounted for 38% of the total suspended load. In contrast, artificial floods only contributed to 1.1%, having low impact on sediment transport. In some years, natural floods may transport up to 75% of total annual suspended load, as was the case of 2007–08. Overall, floods contributed 56% of the inorganic load and 28% of the organic load. During high flows (>600 m^3/s), the percentage of inorganic load increased to 85%, while for low discharges (<600 m^3/s) this value fell to 69%. In contrast, for high flows the organic load represents 15% but increases to 30% for flows less than 600 m^3/s. Therefore, floods in the lower Ebro River have a minor impact in the transfer of the organic matter. This pattern is shown in the histogram of suspended organic and inorganic load (Fig. 8). The histogram shows a bimodal effective discharge (Q_{eff}) for the organic load, with one peak around 200 m^3/s and a second peak close to 500 m^3/s. Q_{eff} is located in the region of low discharges, showing that floods play a minor role in the transfer of the organic material. Nevertheless, a significant (but unmeasured) quantity of organic matter as flotsam (wood debris, macrophytes, etc.) passes the gauging station at high flows. It might be that the flux of organic matter peaks at the highest discharges, considering the large fractions.

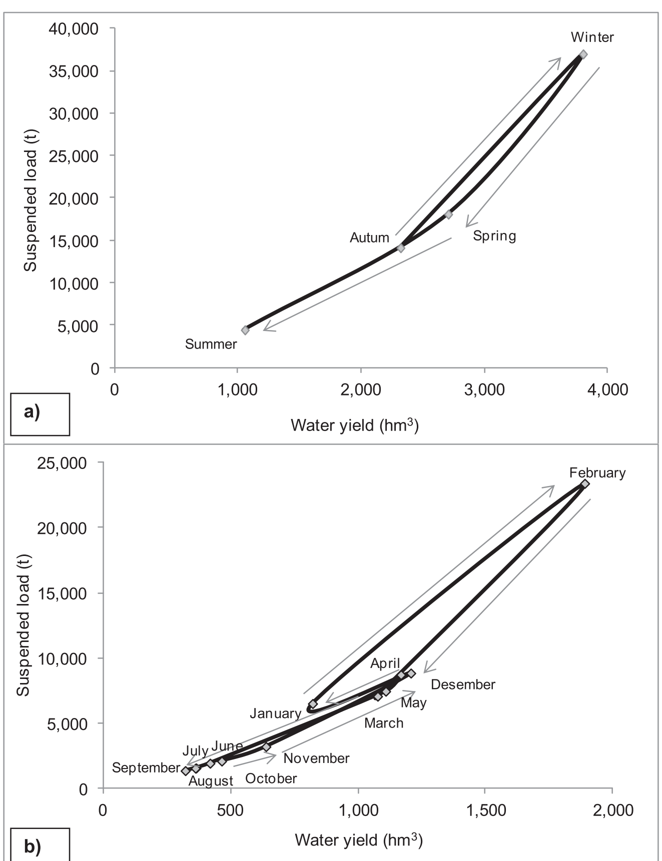

Fig. 7. Seasonal (a) and monthly (b) hysteresis of the suspended load for 2008–09.

The inorganic load also shows a bimodal Q_{eff} with one peak exceeding the bank-full discharge (between 1600 and 1700 m^3/s) and a second peak at the upper end of regular discharges (from 500 to 700 m^3/s) (Fig. 8). The bimodality of Q_{eff} could be associated with both the role of floods, especially those above to bank-full discharge (i.e. 1100 m^3/s) coming from upstream reservoirs, and the frequent releases generated from reservoirs for hydropower production. Hydropower production involves releasing clean water (with low suspended load) from reservoirs. Generated discharges (usually ranging from 300 m^3/s to 700 m^3/s) are large enough to both mobilize suspended solids (preventing the accumulation of fines through the river channel), and erode the river-banks (with the corresponding deterioration of the fluvial system). These discharges transported up to 30% of the total inorganic load, similar to the load transported by discharges above bank-full (which contributed 37% of the inorganic load). However, the frequency of the latter (1%) is much lower than the former (27%). These results agree with those obtained by Wolman and Miller (1960) and Phillips (2002) who pointed out that in some streams at least two discharges play an important role in forming and maintaining channel morphology. One of these is large enough (and well-below-bank-full) to transport and prevent the accumulation of the fines. A second one equal or higher than the bank-full discharge is necessary to transport the coarser bed material and erode the channel banks (Phillips, 2002). The reduction of frequent floods in the lower Ebro River might be reducing the mobilization of bed load towards the delta, likely having a significant impact on delta growth and enhancing coastal erosion. However, the main cause of sediment deficit must be attributed to the trapping effect of reservoirs.

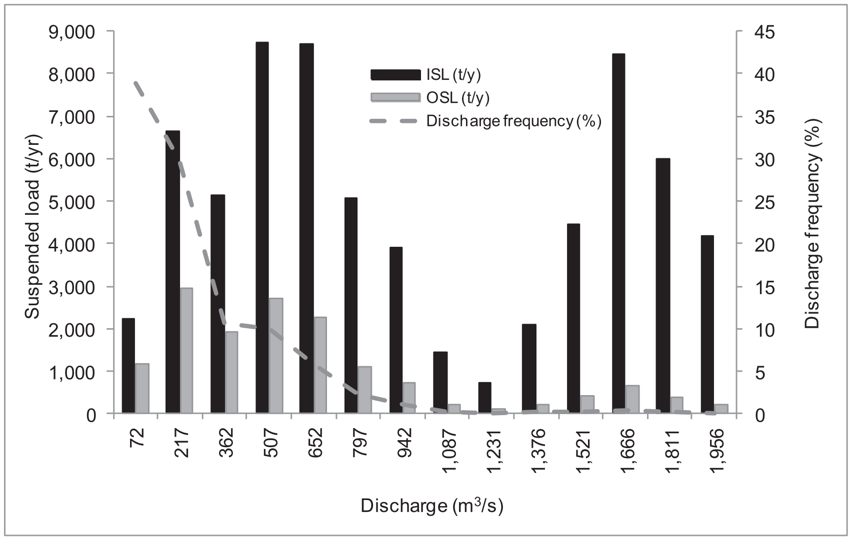

Fig. 8. Organic and inorganic suspended load concentration histograms per discharge class for the Ebro River in Tortosa during 2007–10. Bi-plots show the frequency of discharges (%) within each class and the respective total load in tonnes. The effective discharge is the peak of the organic and inorganic suspended load histogram.

4.4. Water fluxes for 1981–2010

The mean annual water yield for the period 1981–2010 is estimated at 9120 h m^3/y with 289.2 m^3/s mean water discharge and 0.003 m^3/s/km^2 mean specific discharge value. For the whole period (Fig. 9), the maximum water yield was recorded in 1987–88 (18,077 h m^3), being minimum in 2001–2002 (4159 h m^3). There is a strong variability of the water yield between consecutive years (coefficient of variation 35.4%), typical of Mediterranean rivers. Winter is the wettest season contributing to 36.5% of the total mean annual water yield; followed by spring and autumn, with a mean value of 28 and 23.6%, respectively. Summer, which only contributes to 11.9%, is the driest season. Similar results were obtained by Tena et al. (2012) in Xerta. The flow frequency curve (FFC) for the period (1981–2010) indicates that a discharge of 697.9 m^3/s is equalled or exceeded 10% of the time, while a discharge of 102.4 m^3/s is equalled or exceeded 85% of the time.

Mean daily discharge showed a slight significant negative trend ($r_s = -0.028$ N = 10,547; $r_{k\text{-}t} = -0.018$ N = 10,547; $p < 0.05$), likely due to the increase in water demand for irrigation and the evaporation in reservoirs, as well as the increase of forest cover in the headwaters (Gallart and Llorens, 2004). In addition, a significant decreasing trend ($r_s = -0.335$ N = 29; $r_{k\text{-}t} = -0.218$ N = 29; $p < 0.09$) is observed for the number of days with discharges between 336.4 and 187.6 m^3/s (those equalled or exceeded between 50 and 25% of the time); as well for discharges lower than 93 m^3/s (equalled or exceeded 90% of the time) ($r_s = -0.526$ N = 29; $r_{k\text{-}t} = -0.370$ N = 29; $p < 0.05$). This may be partially explained because the application of the minimum environmental flow in the lower Ebro River after 1995. In contrast, a positive significant trend is obtained for discharges ranging between 187.6 and 93 m^3/s (equalled or exceeded between 50 and 75% of time) ($r_s = 0.55$ N = 29; $r_{k\text{-}t} = 0.367$ N = 29; $p < 0.05$), indicating a general trend to the homogenization of the river flow in a narrow range of discharges. Nevertheless, the number and the magnitude of the maximum annual mean daily discharge do not show a significant trend ($r_s = 0.151$ N = 29; $r_{k\text{-}t} = 0.132$ N = 29; $p < 0.05$) ($r_s = 0.149$ N = 29; $r_{k\text{-}t} = 0.116$ N = 29; $p < 0.05$).

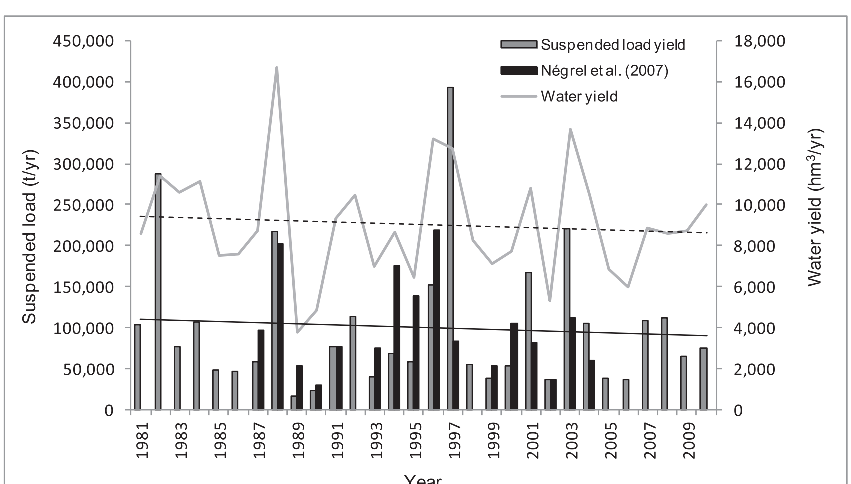

Fig. 9. Reconstructed suspended load budget for the period 1981–2010 at Tortosa, before the river enters the Ebro delta. Pecked line indicates water yield trend; solid line indicates suspended load trend.

4.5. Suspended load fluxes for 1981–2010

Total suspended load transferred during this period is estimated at 2,986,401 t (±537,552 t), giving a mean value of 99,547 t/y (±17,918 t) (1.20 t/km^2/y or 10.9 g/m^3). The trend analysis shows a smooth fall of the annual suspended load mainly related to the slight decline of the annual water yield. However, the trend is not statistically significant ($p > 0.05$) ($r_s = -0.74$ N = 30; $r_{k-t} = -0.48$ N = 30). The obtained value in this study is similar to the reported by Guillén and Palanques (1992) and Négrel et al. (2007). These authors report, respectively, a mean value of 120,000 t/y (1.44 t/km^2/y) for the 1988–90 period and 99,500 t/y (1.2 t/km^2/y) for the 1987–2004 period. Differences are small, but in both studies flood events were not sampled or under sampled. For instance, the study of Guillén and Palanques (1992) took place in 1988–90, a period during which no floods were recorded because it was one of the driest years recorded during the 30 year period. Samples were collected during discharge rates in the range of only 110–675 m^3/s and their estimates are only based on 7 sampling days. In addition, it is not explained how the suspended load was computed. Figures reported by Negrél et al. (2007) were based on the CHE dataset, i.e. from monthly samples without taking into account flood events (unless sampling time coincided). Consequently, only 7 samples corresponded to high discharges (between 900 and 1150 m^3/s), while nearly 90% of the 274 samples were taken for discharges ranging from 100 to 300 m^3/s. Thus, possible biases of suspended load computation relative to sampling frequency, temporal resolution, and errors associated with flux estimate have to be taken into account (i.e. Horowitz, 2002). For instance, infrequent sampling often leads to a large under-prediction while errors trend to decline with increasing temporal resolution, in particular when regular sampling is supplemented by samples collected specifically during flood events (Walling and Webb, 1988). In contrast, low sampling frequency trends to over-estimate the load transferred during low flows (Horowitz, 2002). Walling and Webb (1981) showed a general underestimation by 70% or more when the total load is calculated as the sum of mean monthly SLC values, which are calculated as the product of the mean monthly concentrations and the mean monthly discharge. This computational procedure is similar to the applied by Négrel et al. (2007). Consequently, suspended load values of years above the mean annual water yield (i.e. 1997 or 2003), when large floods were recorded, are expected to show a low estimate when compared to our results. In years below the mean annual water yield (1989, 1994, 2000), suspended load should tend to be higher (Fig. 9). For instance, in the study of Negrél et al. (2007), 1989, 1994 and 1995 (dry years) are, respectively, 228%, 157% and 139% higher in comparison to the present study. In contrast, 1997, 2001 and 2003 (wet years) are, respectively, 79%, 51% and 50% lower than those obtained in this study. From a management point of view, this has severe implications, especially when designing an environmental water and sediment flow regime to achieve suitablle ecological and hydro-morphological status.

The obtained value is also in the same order as reported by Tena et al. (2012) for the 1998–2008 period. These authors estimated a mean value of 155,000 t/y (1.3 t/km^2/y) in a cross section located 40 km upstream of our study section. The observed differences could be mainly associated with the buffering effect (sedimentation in river banks and islands during flood recession) plus methodological differences in sediment sampling and computation. Therefore, suspended load is almost transferred along the lower Ebro River to the delta.

Altogether, the current levels of suspended load in the lower Ebro River are very low and not enough to supply the material needed to maintain the delta elevation and to avoid coastal retreat. The obtained value represents less than 1% of the total suspended load estimated at the end of the 19th century (approximately in 20–30 million t/y). This means that at the end of this century, approximately 45% of the emerged delta will be under mean sea level (Jiménez and Sánchez-Arcilla, 1993). Discharges released from Mequinensa and Riba-Roja reservoirs are designed as a function of hydropower production and water demand (i.e. irrigation cycle), without taking into account the hydro-morphological and ecological needs of the river and delta. The sustainability of the lower Ebro River and its delta could only be guaranteed by the implementation of a new reservoir management concept with the allocation of an appropriate liquid and solid flow regime. The determination of this flow regime requires taking into account a number of processes essential for the system functioning and specific requirements for sediment transport (i.e. pulses) in order to avoid the loss of geomorphic functionality of the river and delta. For that purpose, adequate sampling programs (i.e. with enough frequency, temporal resolution and correct location) are needed.

5. Conclusions

During the last 30 years, the mean suspended load transferred from the river to the sea (estuary) is estimated at 99,547 t/yr (±17,918 t), with no statistically significant temporal trend. Sediment is transferred in two distinct phases: one phase in which the suspended load is delivered into the basin (summer and autumn), followed by a second phase in which most of that load is transferred downstream (winter and spring). These two phases are governed by the relative temporal location of the natural floods. Currently, 80% of the total suspended solids are transferred as inorganic load while the remaining 20% are transported as organic load. Thus, the organic matter plays a minor, but significant role in the sediment load. Floods contributed to 56% of inorganic solid transport, whilst this value falls to 28% for organic load. The current river management from the reservoirs had a direct effect on the suspended load transport creating a huge sediment deficit downstream of the reservoirs (the mean annual suspended load computed represents less than 1% of total suspended load estimated at the end of the 19th century), and producing the existence of a bimodal effective discharge because the frequent releases generated for hydropower production.

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