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Spatial and temporal dynamics of suspended load at-a-cross-section: The lowermost Ebro River (Catalonia, Spain)

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ABSTRACT

Suspended load dynamics were analyzed for the period 2007–2009 in a semi-meandering cross-section under different hydrological conditions. Samples were collected at four different points of the cross-section. During "low discharges" ($\leq$600 m^3/s) suspended load samples were collected at-a-monthly basis, whereas at "high discharges" ($>$600 m^3/s) sampling was conducted intensively (at-a-daily basis during the first stages of the flood event). Results indicated that during low discharges, both organic and inorganic suspended load concentrations tended to be uniformly distributed across the fluvial section; but during high discharges, two distinct areas were found: an area extending from the "Inner-bank" to the "Channel centre" (Area-I) with higher suspended concentrations (organic and inorganic) than those recorded in the "Outer bank" (Area-II). This phenomenon was likely related to the formation of secondary flow velocity cells and the activation of new sources of sediment. In addition, a non-significant relationship between organic suspended load and water flow was observed in the outer-bank. At-a-monthly basis, the analysis of the suspended load showed the existence of an intra-annual cycle of the inorganic concentrations, with a progressive increase from October to March followed by a decrease from March to September. Nevertheless, the organic suspended load did not show any trend, being equally distributed along the year, suggesting that other sources of organic matter besides phytoplankton are predominant.

1. Introduction

Rivers are significant geomorphologic agents in transferring water and sediment from the land surface to the oceans. In such function, two major mechanisms are available to explain the natural transport of sediments: the transport in the bed layer and the transport of suspended load (Maza-Álvarez and García-Flores, 1996). Generally, suspended load is the largest fraction of the load moved by the river and commonly represents up to 90% of the total load exported. That load is maintained into suspension by the vertical component of turbulence in flowing water.

In low-land rivers suspended load concentration at a given point may not be the same as the concentration at another point or as the mean concentration for the whole section (Thomas, 1985). Short-term variations in hydraulic parameters (e.g. velocity gradient), as well as in sediment sources (i.e. hysteretic phenomenon) or transport dynamics (e.g. bed-forms), leads to the variability of suspended solid concentrations over space and time (e.g. Asselman, 1999; Alexandrov et al., 2003; Hudson, 2003), as well as, in longitudinal and in transversal directions (Lewis and Saunders, 1984; Horowitz et al., 1989; Hunter, 1997). Consequently, the complexity of fluvial suspended load processes difficult

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obtaining representative and high quality data (Edwards and Glysson, 1999). Furthermore, the required measurements and related analyses of sediment data are expensive and highly labour intensive (Collins et al., 1998). As a result, several studies have focused on the assessment of suspended-load data accuracy (e.g. Bonacci, 1981; Burkham, 1985); the effects of sample collection (e.g. Phillips and Walling, 1995); the comparison of existing suspended-load measurement techniques for the selection and use of the adequate measurement equipment (Wren et al., 2000); or the development of new techniques for sampling suspended material (e.g. Phillips et al., 2000). Nevertheless, little attention has been paid to investigate the spatial cross-sectional suspended load variations (e.g. Lewis and Saunders, 1984; Horowitz et al., 1989; Gupta and Chakrapani, 2007) despite its importance in, for instance, the effects on water quality (Golterman et al., 1983), fish habitat (e.g. Gregory and Levings, 1996; Vogel and Beauchamp, 1999), transport of nutrients, tracer metals and other contaminants (e.g. Allan, 1979; Horowitz et al., 2001).

Traditionally, geomorphologists and hydrologists have focused on the total suspended load without discerning between organic and inorganic fractions. In some cases, hydromorphologists have discarded organic components from suspended load samples focussing on the behaviour of the inorganic fractions at proper spatiotemporal scales for the development of sediment-rating curves and estimation of sediment yields, often as an indicator of changing land uses (Beschta, 1981). In contrast, the interest of stream ecologists on sediments has often focused on the role of suspended load in water quality degradation, for example its deleterious impacts on biological communities (e.g. Waters, 1995), or the role of organic suspended load in providing food resources for aquatic biota from headwater to downstream reaches (e.g. Wallace and Grubaugh, 1996). Therefore, stream ecologists often have discarded information on the mineral fraction, being concentrated on the importance of the organic fraction of suspended load (Wilzbach et al., 2009). Consequently, the failure to distinguish between organic and inorganic components of the suspended load or to consider the full suite of information present in suspended load samples has hindered a full understanding of sediment dynamics as it affects stream health and reflects watershed condition (e.g. Minshall, 1996). Thus, a general lack of studies determining the organic and inorganic concentrations and dynamics exists, especially in large rivers.

Over the last two decades, several studies have been carried out in the lower Ebro River and its estuary in order to analyze, among other subjects, the sediment transport dynamics and hydrodynamics (e.g. Guillen and Palanques, 1992; Vericat and Batalla, 2005, 2006; Vericat et al., 2006; Tena et al., 2011); the effects of reservoirs in the sediment transport (e.g. Varela et al., 1986; Ibáñez et al., 1996, 2012; Sanz et al., 1999; Batalla et al., 2004, 2006); the water and sediment management from reservoirs (e.g. Ibáñez et al., 1997; Ibàñez and Prat, 2003; Rovira and Ibáñez, 2007; Batalla and Vericat, 2009), and the past and present Ebro Delta evolution (e.g. Jiménez and Sánchez-Arcilla, 1993; Jiménez et al., 1995; Canicio and Ibáñez, 1999). Despite the existence of these studies, the suspended load dynamics before entering the Ebro delta remains largely unknown. The current study aims to examine the spatial and temporal suspended load dynamics at-a-cross-section in the lowermost parts of the Ebro River (the largest river of the Iberian Peninsula). Analyses are based on intensive field observations collected during two consecutive years. Of particular interest is the exploration of both organic and inorganic suspended load dynamics under different hydrological conditions (e.g. low and high discharges).

2. Materials and methods

2.1. Study site

The study has been carried out in the lowermost reach of the Ebro River (drainage area 85,534 km^2), during the hydrological years 2007/2008 and 2008/2009. The study section is located in Tortosa (drainage area 83,093 km^2), 170 m downstream of a bend (Fig. 1) in a 116 m channelized section, which precludes both the lateral mobility of the river banks and the overflow of the alluvial-plain. At the right-bank there is a well-developed point bar. In the study cross-section, the bed surface sediment ranges in size from very fine gravel to small cobbles. Grain sizes are sorted by location, becoming coarser from the lateral point bar ($D_{50\ \mathrm{surface}} = 12.5$ mm) to the opposite riverbank (26.3 mm), yielding a mean riverbed surface D_{50} of 18 mm. The mean hydraulic-channel slope is estimated at 0.0005; and bank-full discharge ($\approx 1100\ m^3/s$; based on 1.5 return period) is equalled or exceeded 3.5% of the time (period 1968–2004) (Batalla et al., 2004).

During the study period the mean annual water yield was calculated in 8609 hm^3; well below the long-term average (11,317 hm^3/yr) of the last decades. The period is thus classified as dry. Annually (October–September) the water yield was 7357 hm^3 in 2007–2008 and 9861 hm^3 in 2008–2009. The mean discharge for the period 2007/2009 was 272 m^3/s, giving a mean specific value of 0.003 $m^3/s/km^2$. The flow was highest in May (540 m^3/s), and lowest in July (132.5 m^3/s).

2.2. Data collection

The sampling programme was based on hydrological conditions and divided into “low discharges” ($\leq 600\ m^3/s$) and “high discharges” ($>600\ m^3/s$). This threshold flow condition was defined as the critical discharge for the entrainment of surface riverbed particles, established from bed load samples collected at two different points of the river cross-section. Samples were collected by means of a Helley–Smith sampler (29 kg weight, 76.2 mm inlet and mesh size diameter 0.45 mm), and below 600 m^3/s no riverbed particle movement was observed. During “low discharges” suspended load samples were collected at-a-monthly basis (although occasionally the interval time was reduced in order to incorporate the maximum number of sampled flows). For “high discharges” sampling was conducted intensively (e.g. at-a-daily basis during the first stages of the flood event). Sampling points were established avoiding the potential effects of the bridge located in the study cross-section (Fig. 1). Hence, points were settled, from the right-bank of the cross-section, as follows: 18 m (hereafter, Inner-bank or Ib); 40 m (Inner-bank-Centre channel or Ib–Cc); 55 m (Centre channel or Cc) and, 108 m

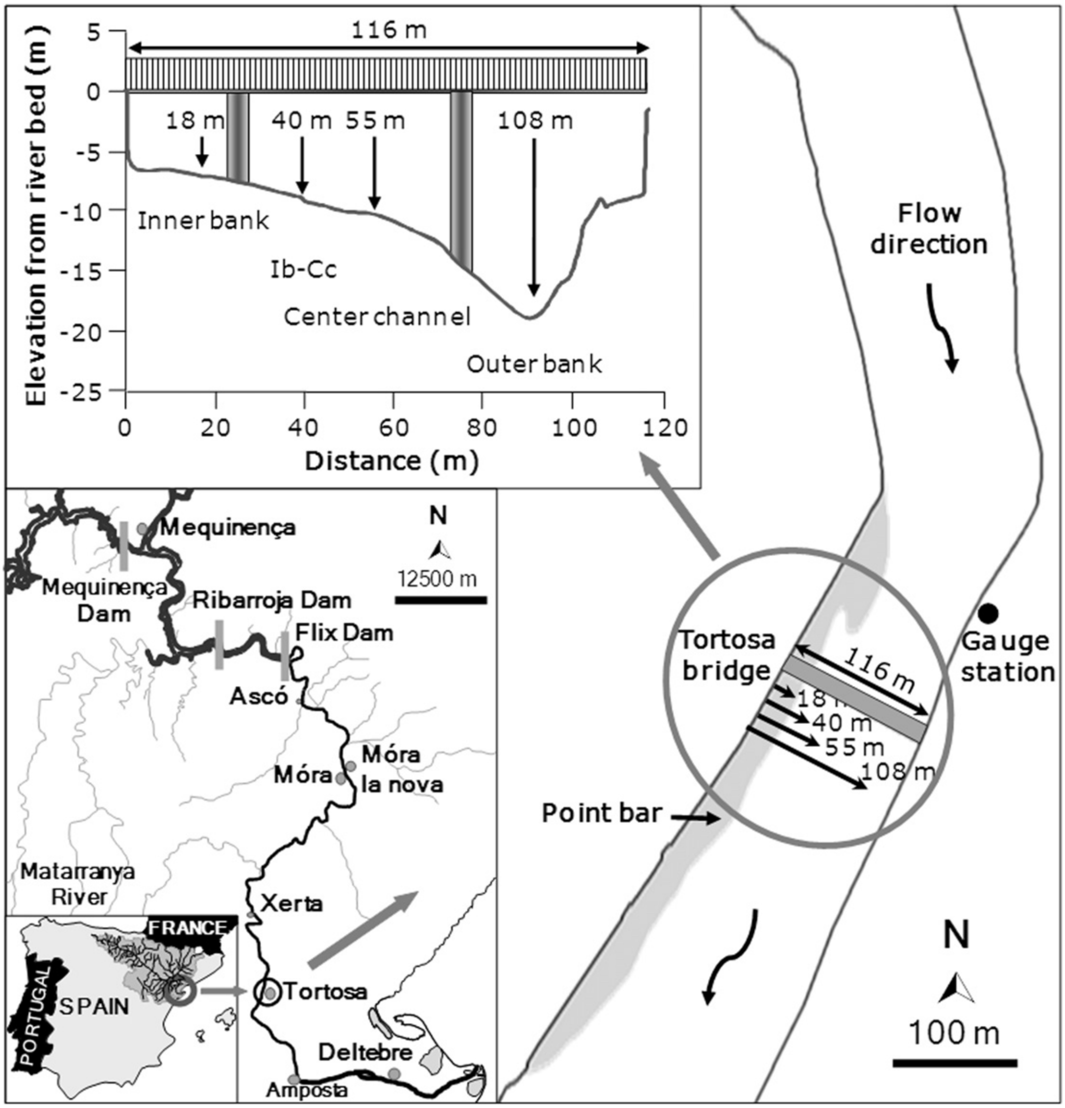

Fig. 1 – Localization of the study section in the Ebro River basin (NE Iberian Peninsula) and sketch plan of the study section.

(Outer-bank, or Ob). Unfortunately, for discharges above 1500 m^3/s we were not able to sample the Ob because of the extreme flow conditions (e.g. mean flow velocity up to 2.5 m/s for a discharge of 770 m^3/s) and the massive presence of material transported in flotation (e.g. debris wood or macrophytes) preventing us from carrying out the sampling under secure conditions. In general terms, no significant water discharge variations were observed within each sampling day because of the flow regulation from reservoirs.

Integrated water samples were obtained by means of a 29 kg cable-suspended depth-integrating US D74. For discharges below 1500 m^3/s, sampling was performed from a boat. During flows above 1500 m^3/s, the sampler was lowered from a bridge using a mobile crane placed at 8 m above water level. During “low discharges” two successive sequential measurements per vertical were carried out at four verticals. During “high discharges” from three to five traverses (depending on the water stage) were carried out to account for temporal variations. Once the first traverse was finished, the second traverse was initiated starting from the first vertical sampling point. Sampling was always performed from the Ib to the Ob sampling point. 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 (the interval that elapses between consecutive samples) 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. A volume of 0.75 L of water was collected per sample. During the first 3 days, the sampling frequency was more intense, decreasing over the following days. This sampling scheme was designed to capture the maximum variations in hydraulic parameters (i.e. flow velocity, depth and width of the channel) observed during the first flood stages.

Water discharge was obtained from the gauging station located 130 m upstream from the cross-section. For discharges below 1500 m^3/s, flow velocity was measured at 60% of the water column depth by means of a current-meter (model Valeport Braystoke BFM001). At least, three successive flow measurements were made at the same locations where samples were taken. Overall, 264 depth integrated water and suspended load samples were collected during the two study years. We were considering all suspended load 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 load such as Emmett (1979), among others, established from his work at the Oak Creek (Oregon, USA).

Water and suspended load samples were filtered by using 45 μm cellulose filters in a 24–48 h time lag. Before filtering, filters were washed with distilled water and burned at 450 °C for 5 h. Total suspended load concentrations were computed from the differences in filter weight (pre- and post-filtering). Once filters were dried (at room temperature) and weighed, these were burned at 450 °C for 4 h to determine the total inorganic and organic matter contained in each sample (ASTM, 1997). Grain size distribution of the samples was not carried out since the previous work of Muñoz and Prat (1989) showed that most of the particulate material transported in suspension in the lowermost Ebro River is very fine (between 0.45 and 50 μm).

2.3. *Statistical analysis*

Principal component analysis (PCA) was applied to explore the patterns of association among hydraulic and sedimentological variables. Kaiser–Meyer–Olkin's (KMO) measure of sampling adequacy was used to assess the usefulness of a PCA. KMO ranges from 0 to 1 and should be >0.5 if variables are sufficiently interdependent for PCA to be useful (Tabachnick and Fidell, 2001). Differences in both organic and inorganic suspended load concentration among sampling points were first analyzed with multiple analysis of covariance (two-way MANCOVA), using water flow as covariate. Multivariate analysis of variance (two-way MANOVA) was also used to compare suspended load concentrations (organic and inorganic) among sampling points and between discharge types (high and low discharges). MANOVA is used when several dependent variables are measured on each sampling unit instead of only one variable. MANOVA compares the mean vectors of k groups, whereas equality of the mean vector implies that the k means are equal for each variable. If two means differ for just one variable then it is concluded that the mean vectors of the k groups are different (Sokal and Rohlf, 1995). MANCOVA is similar to MANOVA, but controlling for the effects of continuous independent variables, the covariates. In addition to P values, the partial eta squared (η_p^2) was used as a measure of effect size. Like the regression coefficient (r^2), η_p^2 is the proportion of variation explained for a certain effect (effect sum-of-squares (SS)/(effect SS + error SS)), and has the advantage over eta squared (effect SS/total SS) of not depending on the number of sources variation used in the ANOVA (i.e. it could be compared among different designs), because it does not use the total SS as the denominator (Tabachnick and Fidell, 2001). In contrast to P value, the η_p^2 has the advantage that allows the proper comparison of treatments (e.g. lower P value does not necessarily mean that a factor has stronger effect) (Alcaraz et al., 2008). To further describe the variation of both organic and inorganic concentration along the hydrological cycle (month 1 corresponding to October), generalized additive models (GAMs) (Lepš and Šmilauer, 2003) were also fitted. GAMs are an extension of the generalized linear models that, unlike more conventional regression methods, do not require the assumption of a particular shape for the response variable distribution along the environmental gradient (Lepš and Šmilauer, 2003). Model complexity was selected by the stepwise selection procedure using the Akaike information criterion (AIC). The AIC not only considers the goodness of fit but also parsimony; penalizing very complex models (Burnham and Anderson, 1998).

Prior to analysis, all quantitative variables were transformed to improve homoscedasticity and linearity. All statistical analyses were performed with SPSS 18.0, except for GAMs where R software 2.12.0 with GAM 1.03 library was used.

3. Results

3.1. *Dynamics of organic and inorganic suspended load concentrations at-a-cross-section*

The PCA showed that the main trend was an increment of sediment load with water flow (Fig. 2). As expected, all of the analyzed variables were interdependent and significantly highly correlated among them (Table 1). The KMO's measure of sampling adequacy (0.72) indicates the usefulness of the PCA, with the first two axes explaining, respectively, 75.2% and 14.8% of the total variation (Fig. 2). The strongest correlations were found between suspended organic and inorganic concentration; and between suspended inorganic concentration and water discharge (Table 1). These variables were all positively correlated among them and opposed to percent of suspended organic load (Table 1; Fig. 2). The first PCA axis summarized these correlations displaying a seasonal gradient

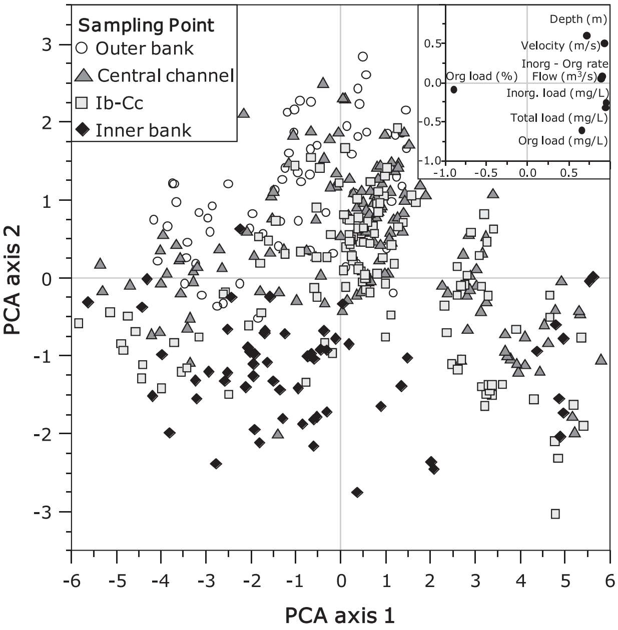

Fig. 2 – Principal component analysis (PCA) of the measured hydrological variables. Factor loadings of the variables (●) and sampling point scores on the first two principal component axes are shown.

Table 1 – Pearson's correlation coefficients between hydraulic and sedimentological variables recorded in the Ebro River cross section.

Variable	Depth (m)	Flow (m^3/s)	Inorganic load (mg/L)	Organic load (mg/L)	Total load (mg/L)	Organic rate (%)	Velocity (m/s)
Flow (m^3/s)	0.419^c						
Inorganic load (mg/L)	0.389^c	0.817^c					
Organic load (mg/L)	0.147^a	0.479^c	0.765^c				
Total load (mg/L)	0.373^c	0.785^c	0.990^c	0.835^c			
Organic rate (%)	-0.406^c	-0.815^c	-0.863^c	-0.350^c	-0.806^c		
Velocity (m/s)	0.820^c	0.735^c	0.593^c	0.192^b	0.559^c	-0.635^c	
Rate inorg. – org. load	0.395^c	0.787^c	0.856^c	0.367^c	0.811^c	-0.992^c	0.609^c

a < 0.01.
b < 0.001.
c < 0.0001.

mostly related to flow discharge, from the driest (August) to the wettest month (May). The second PCA axis distinguished a-cross-section gradient, from the outer-bank (with highest depth and velocity but lowest organic and inorganic suspended load concentrations) to the inner bank (with lowest depth and velocity but highest organic and inorganic suspended load concentrations). The central parts of the fluvial channel appeared as transitional points (Fig. 2). In addition, the PCA indicated that during low discharges suspended load concentrations were similar across the section; but an increase in flow discharge resulted in a differentiation from the outer-bank to the rest. Accordingly, under high flows, the Ib, Ib–Cc and Cc sampling points showed similar organic and inorganic concentrations (Fig. 2).

The MANCOVA test indicated that suspended load concentration significantly depended on water flow (Wilks's $\lambda = 0.34$; $F_{2,\ 394} = 383.6$; $P < 0.0001$); but differed significantly among sampling points (Wilks's $\lambda = 0.93$; $F_{6,\ 788} = 5.09$; $P < 0.0001$) and sampling point × water flow interaction (Wilks's $\lambda = 0.92$; $F_{6,\ 788} = 5.80$; $P < 0.0001$). These differences were mainly explained because for a given flow, suspended load concentrations tended to be lower at the Ob than in Ib, Ib–Cc and Cc sampling points (Figs. 2 and 3), according to the fitted regression lines, the interception point is situated at ca. 250 m^3/s for both organic and inorganic suspended load (Fig. 3). Therefore, when the Ob point was excluded from the MANCOVA analysis, differences among sampling points and their interaction were not significant ($P = 0.50$ and $P = 0.42$, respectively) (see also Table 2). The ANCOVA test confirmed this pattern (Table 2). Results also revealed that both organic and inorganic concentration significantly differed among sampling points (MANOVA, Wilks's $\lambda = 0.96$; $F_{6,\ 788} = 2.53$; $P = 0.019$), discharge type (Wilks's $\lambda = 0.64$; $F_{2,\ 394} = 110.6$; $P < 0.0001$) and, marginally, their interaction (Wilks's $\lambda = 0.97$; $F_{6,\ 788} = 2.06$; $P = 0.056$). These differences were mainly explained by the discharge type ($\eta_p^2 = 0.40$); since the sampling point and their interactions had a minor weight ($\eta_p^2 = 0.02$ and $\eta_p^2 = 0.01$, respectively). The univariate tests (ANOVA) indicated that sampling point differences were related to the Ob sampling point (Table 3). In fact, in the Ob sampling point the discharge type had a lower significantly positive effect on inorganic load concentration (ANOVA; $F_{2,\ 330} = 21.75$;

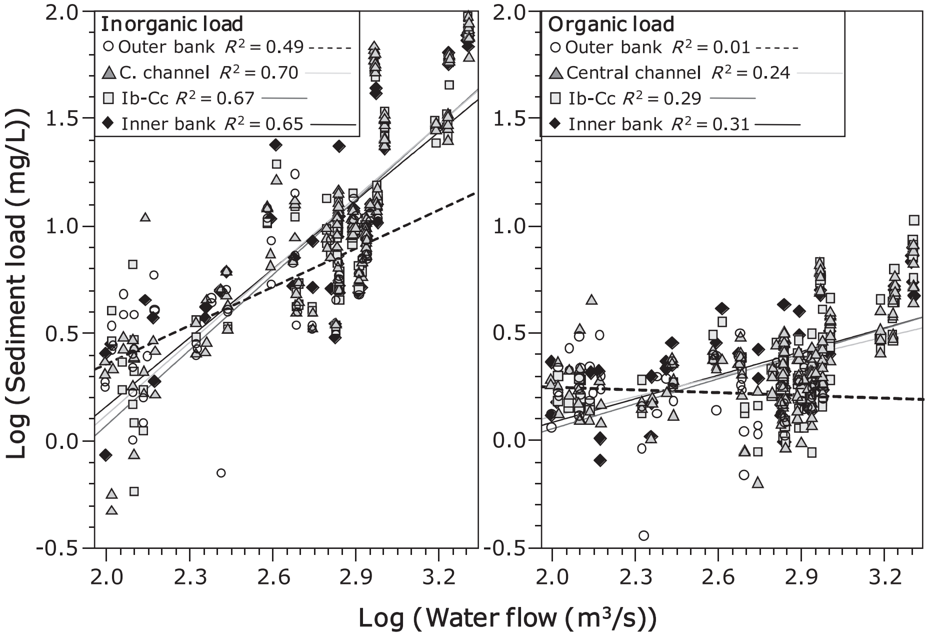

Fig. 3 – Relationship of both inorganic (left) and organic (right) suspended load per sampling point with water flow.

Table 2 – ANCOVAs of the sediment loads at-the-cross-section of the lower Ebro River per sampling point (factor) and water flow (covariate) (top) and excluding Ob sampling point from the analysis (bottom).

Variable	Explained variation (adjusted R^2)	Among points			Log (Q (m^3/s))			Among points × Log (Q (m^3/s))		
		$F_{3,\ 395}$	P	η_p^2	$F_{1,\ 395}$	P	η_p^2	$F_{3,\ 395}$	P	η_p^2
Log (inorganic load (mg/L))	0.686	8.38	<0.0001	0.06	37.36	<0.0001	0.60	9.34	<0.0001	0.07
Log (organic load (mg/L))	0.281	8.31	<0.0001	0.06	2.45	<0.0001	0.16	9.64	<0.0001	0.07
		$F_{2,\ 331}$	P	η_p^2	$F_{1,\ 331}$	P	η_p^2	$F_{2,\ 331}$	P	η_p^2
Log (inorganic load (mg/L))	0.673	0.36	0.70	0.002	39.83	<0.0001	0.65	0.34	0.71	0.002
Log (organic load (mg/L))	0.261	0.60	0.55	0.004	3.94	<0.0001	0.25	0.68	0.51	0.004

$P < 0.0001$); but not on organic load ($P = 0.58$) (Fig. 4). In contrast, the Ib, Ib–Cc and Cc sampling points showed a significant increment of both inorganic and organic suspended load concentrations during high discharges (MANOVA; Wilks's $\lambda = 0.61$; $F_{2,\ 330} = 106.4$; $P < 0.0001$) (Table 2 and Fig. 4); with no differences in concentration among sampling points ($P = 0.88$) or sampling point × discharge type interaction ($P = 0.71$) (Fig. 4 and Table 3). Hence, during low discharges, the four sampling points showed similar values of both organic and inorganic suspended load concentrations; but during high discharges the increase of inorganic concentration tended to be higher in Ib, Ib–Cc and Cc than in Ob (Fig. 4). As a result, a differential behaviour of the suspended load concentrations at-a-cross-section was inferred during high discharges and two well-differentiated areas along the cross-section were defined: one area including the Ib, Ib–Cc and Cc sampling points (hereafter Area-I), and a second area including the Ob sampling point (Area-II). Area-I showed higher concentrations of both organic and inorganic loads during high discharges, but lower flow velocity and water depth.

3.2. *Intra-annual variation of the organic and inorganic suspended load concentrations*

At-a-monthly bases, the analysis of the suspended load concentrations showed the existence of an intra-annual cycle of the inorganic load. The response curves (GAMs) of inorganic suspended load concentrations illustrated a clear relationship with the hydrological fluvial regime (Fig. 5). The AIC test selected a unimodal response for inorganic concentration for both Area-I (Deviance = 2.99, non-linear $F_{1,\ 21} = 4.78$, $P = 0.040$), and Area-II (Deviance = 1.17, non-linear $F_{1,\ 21} = 4.35$, $P = 0.049$), with inorganic suspended load concentrations peaking in February–March (Fig. 5). Accordingly, the inorganic concentrations increased progressively from October (hydrological month 1) to March and decreased from March to September. Nevertheless, for the organic concentrations, GAMs analysis did not selected any model performing better than the null model (intercept only) (Deviance = 0.61 for Area-I and 0.45 for Area-II), indicating that the organic suspended load concentrations were equally distributed along the year; being always higher in Area-I than in Area-II (Fig. 5). Consequently, the sediment composition followed an annual cycle with an increase in the percentage of the inorganic suspended load (non-linear $F_{1,\ 20} = 4.71$, $P = 0.021$, and non-linear $F_{1,\ 20} = 5.63$, $P = 0.011$ for Area-I and Area-II, respectively) and a decrease in the percentage in the organic suspended load from October to March (Fig. 5).

4. Discussion

Several studies (e.g. Vanoni, 1977; Ongley and Blachford, 1982; Horowitz et al., 1989) have shown that the major source of variation of the suspended load concentration at-a-cross-section is related to particle sizes coarser than 62 μm. In contrast, fractions below 62 μm are homogeneously distributed along the fluvial channel. These particles sizes are mainly controlled by the supply of this material while sand fractions are mainly originated from erosion of the bed and banks of the river. Thus, the amount of sand (>62 μm in particle size) in the suspended load is directly proportional to the turbulence and an increment of flow discharge is corresponded with a suspension of sand (lifted from riverbed and banks) because the turbulent forces (Ongley, 1996). Karlsson

Table 3 – ANOVAs of the sediment loads at-the-cross-section of the lower Ebro River per sampling point and discharge type (top) and excluding Ob sampling point from the analysis (bottom).

Variable	Explained variation (adjusted R^2)	Among points			Discharge type			Among points × discharge type		
		$F_{3,\ 395}$	P	η_p^2	$F_{1,\ 395}$	P	η_p^2	$F_{3,\ 395}$	P	η_p^2
Log (inorganic load (mg/L))	0.398	3.48	0.016	0.03	160.8	<0.0001	0.29	0.13	0.013	0.03
Log (organic load (mg/L))	0.131	4.90	0.002	0.04	19.65	<0.0001	0.05	3.28	0.021	0.02
		$F_{2,\ 331}$	P	η_p^2	$F_{1,\ 331}$	P	η_p^2	$F_{2,\ 331}$	P	η_p^2
Log (inorganic load (mg/L))	0.353	0.23	0.79	0.001	154.6	<0.0001	0.31	0.91	0.40	0.005
Log (organic load (mg/L))	0.188	0.40	0.67	0.002	29.2	<0.0001	0.10	0.32	0.72	0.002

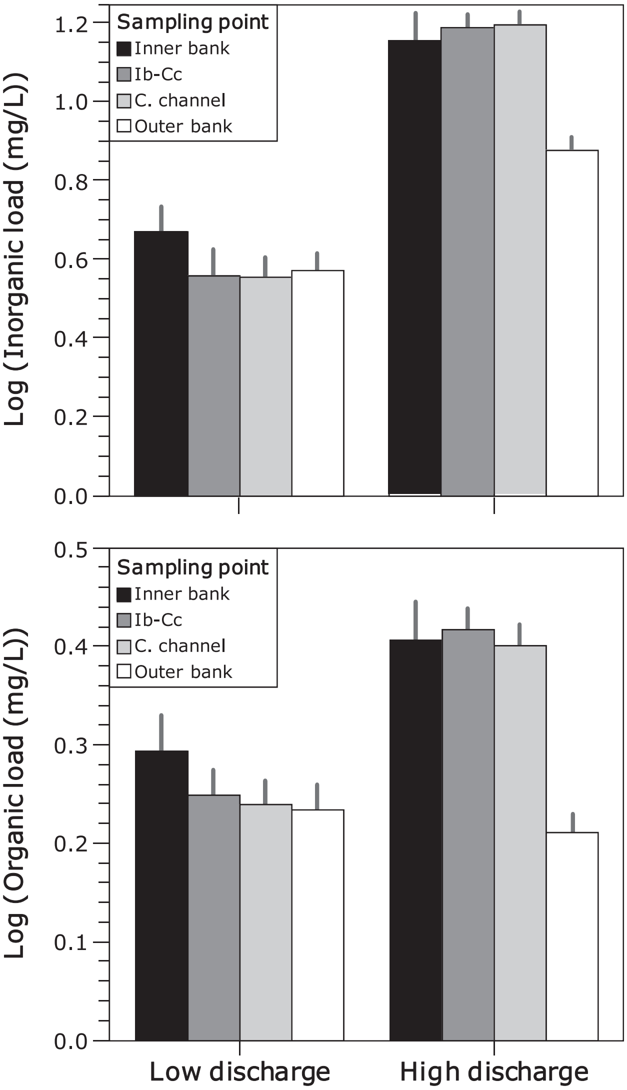

Fig. 4 – Effect of discharge type (“low” ≤ 600 m^3/s and “high” > 600 m^3/s) on the inorganic (top) and organic (bottom) suspended load for the four different sampling points. Error bars show the standard error of the mean by point. See Table 2 for statistical details.

and Rahmberg (1999) observed this dynamics in the Odzi River (Zimbabwe), relating the lateral distribution of the suspended sediment concentrations to the sand fractions that were lifted from the bed into suspension because the turbulent eddies and the morphology of the fluvial channel. In a similar way, Asselman (1999) in the Rhine River (German) described that once a certain discharge threshold was exceeded, sediment supply to the river increased, and sediment was picked up from the riverbed, resulting in a rapid increase in suspended sediment concentrations. In the Ebro River, results showed that during low flows, suspended load concentrations tended to be homogeneous across the section. However, once a critical discharge was exceeded (i.e. 600 m^3/s), two well-differentiated areas were observed. The progressive incorporation of sand fractions that are lifted from the riverbed, as well as the activation of new sources of sediment (e.g. river banks, point bars, etc.), probably explained this differential behaviour of suspended concentrations during low and high discharges. Further data are needed to document the different patterns of suspended load incorporation and vertical distribution into the river flow.

Our results also showed a differential behaviour of the suspended load concentration from the outer-bank to the inner-bank, mainly during high flows. These results differed from those obtained by Horowitz et al. (1989) and Lewis and Saunders (1984) who observed the lowest suspended load concentrations in samples closest to the banks because of the higher velocities of the river near its core. However, in river bends, an increase of water discharge results in a super-elevation of water at the outer-bank bend. Consequently, a pressure gradient is developed across the section forming a compensatory secondary flow from the outer-bank (high pressure) to the inner-bank (low pressure) of the curve (i.e. Hickin, 1978; Markham and Thorne, 1992; Hooke, 1997), moving sediment from the external to the internal bank (Dietrich and Smith, 1983, 1984) where it is normally deposited forming a point bar (Charlton, 2008). In the analyzed section of the lowermost Ebro River two elements support the hypothesis of the secondary flow formation: first, the presence of a well-developed point bar at the inner-bank of the river bend; and second, the existence of a differential behaviour (from the outer to the inner) of the suspended load concentrations. Based on these observations, it is hypothesized that an increment of the water discharge stands for the formation of secondary flow velocity cells that tend to transfer the suspended load from the Ob to the Ib. However, a detailed study of flow velocity profiles is needed to confirm this hypothesis.

Altogether, the transport pattern of organic suspended load differed from that of inorganic load. More inorganic sediment is entrained and transported during high discharges, so organic matter as a component of the suspended load is not dominant. In contrast, the organic particulate material largely contribute to the total suspended load during base flow, because it is only one-third the bulk density of the inorganic fraction and have a higher surface-to-volume ratio (Sedell et al., 1978). Accordingly, organic particles stay in suspension longer than inorganic particles, and so once entrained in the water column, they tend to remain suspended (e.g. Madej, 2005). Consequently, organic suspended load is more related to the supply than to the hydraulics, as it is reflected in the weak relationship between suspended organic concentration and discharge (Mayorga and Aufdenkampe, 2002; Townsend-Small et al., 2008; Mollá et al., 2006). The percentage of organic suspended load decreased with increasing discharge; passing from a mean value of 32% during low discharges to 14% during high discharges. Even though the percentage of organic fraction decreased with increasing water discharge, the mass transport of organic load increased because of the increasing volume of water indicating that most transport occurs during high flows as reported by Madej (2005) or Wilzbach et al. (2009).

At-a-monthly bases, the analysis of the suspended load concentration showed the existence of an intra-annual cycle of the inorganic load similar to that described by Tena et al. (2011) in a section located 40 km upstream of the study

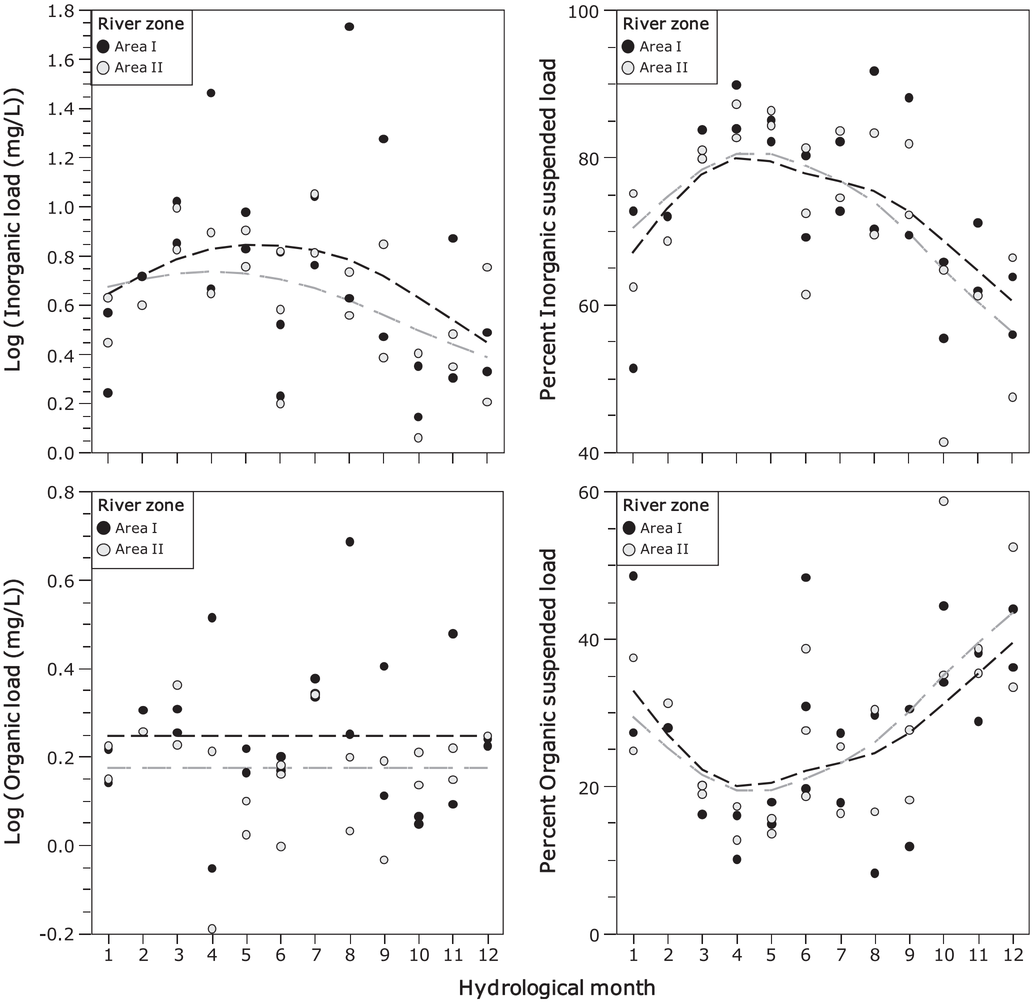

Fig. 5 – Response of inorganic (top) and organic (bottom) suspended load with hydrological month (1 = October) for the two different areas. Lines are the generalized additive models selected by the Akaike information criterion (AIC).

section, where suspended sediment concentration increased from October to May and decreased from May to September, because the number and magnitude of the floods recorded, and the progressive exhaustion of the fine sediment during the succession of floods. Similar sequences were described in the Rhine River (Germany), Panuco River (Mexico) and in the Tordera River (Spain) (Asselman, 1999; Hudson, 2003; Rovira and Batalla, 2006, respectively).

Results also pointed out that the organic suspended load concentration was equally distributed along the year. In the 1960s, the construction of large dams in the lower Ebro (Ibáñez et al., 1996) represented a significant retention of particulate material; for instance, Roura et al. (2008) reported that 97% of the inorganic suspended load and 45% of particulate organic matter is retained in the Mequinensa Reservoir (located ca. 69 km upstream from the studied river section). Also, the intensification of human activities together with the suspended sediment retention into the reservoirs leads to an increase of nutrients until the beginning of the 1990s. But, during the last 20 years, the significant decrease in dissolved phosphorus caused the decrease in phytoplankton and the subsequent spread of macrophytes (mainly *Potamogeton pectinatus*) downstream of the reservoirs (Ibáñez et al., 2012). Consequently, the lower Ebro River has recently undergone an ecosystem shift from a phytoplankton-dominated to a macrophyte-dominated system (Ibáñez et al., 2012) producing a decrease in the organic matter content and a more regular temporal pattern.

5. Conclusions

1) At low flows, the organic and inorganic concentrations transferred in suspension across the fluvial section tended to be homogeneous. Consequently, the circulation of the suspended load along the cross-section is expected to be uniformly distributed.
2) During high flows, two distinct areas within the cross-section were found: an area extending from the Ib to the Cc (Area-I) where suspended concentrations (both organic and inorganic) tended to be higher than those recorded in the Cc–Ob section (Area-II). This dynamics could be

associated to the formation of convective cells that tend to transfer the suspended load from the Ob to the Ib, and the suspension of the sand particles located in the riverbed. Therefore, a general tendency to an utmost circulation of both organic and inorganic suspended load through Area-I is expected.

3) At-a-monthly basis, organic suspended concentrations did not show a concentration–month relationship; being equally distributed along the year. In contrast, inorganic suspended concentration indicated the existence of a seasonal trend with a maximum during winter and a minimum during summer months.

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