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Suspended sediment transfer during a flood along the dam-regulated Segre river (NE Iberian Peninsula)

Transporte de sedimento en suspensión durante una crecida en un río regulado: el río Segre (NE Península Ibérica)

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Abstract

Suspended sediment transport has crucial functions along the river ecosystem and the disruption of its transport has morphological, ecological and economical effects. In this study we have designed a near basin scale sampling and monitoring approach in order to study the effects of the Oliana-Rialb dam complex on the suspended sediment dynamics and transport in the River Segre (13,000 km^2 basin located in NE Iberian Peninsula) during a five-year return period flood event (peak flow of 776 $m^3 \cdot s^{-1}$) occurred in May 2008. The approach presented here allowed estimate the sediment load passing the lowermost part of the basin and ultimately, being supplied to the main River Ebro upstream the Riba-roja dam. Results show that the two large reservoirs in the Segre River retained almost all the suspended sediment carried by the flood (between 75% and 97%). Downstream from the dams, in-channel and bank sediments were mobilized thus progressively increasing the sediment load in the downstream direction and mitigating the deficit of sediment caused by the dams. The five-year-return-period analysed flood transported the 26% of the annual suspended sediment load at the lowermost River Ebro, one of the largest rivers in the Iberian Peninsula. This study shows that Oliana and Rialb reservoirs have a great influence in the transfer of suspended sediment in the Segre River and that this influence could be modified in some extent through dams' management, maximizing the transfer of sediment downstream and reducing the effects of the sediment deficit caused by the impoundment.

Keywords: Segre River, flood event, suspended sediment, reservoirs, turbidity, retention.

Resumen

El sedimento en suspensión cumple funciones esenciales en el ecosistema fluvial; por tanto, su interrupción tiene consecuencias morfológicas, ecológicas y económicas. Este estudio presenta el muestreo y seguimiento de los efectos del sistema de presas Oliana-Rialb sobre la dinámica de sedimento en suspensión en el río Segre (13.000 km^2, NE Península Ibérica) durante una crecida de cinco años de período de retorno (776 m^3• s^{-1}) ocurrida en Mayo de 2008. Los métodos utilizados permitieron estimar la carga sedimentaria que pasó por la parte baja de la cuenca y que llegó al río Ebro aguas arriba de la presa de Riba-roja. Los resultados muestran que los embalses retuvieron casi todo el sedimento en suspensión transportado por la crecida (entre el 75% y el 97%). Aguas abajo de las presas, se movilizaron sedimentos del lecho y de los márgenes, que causaron el aumento progresivo de la carga y, por tanto, mitigaron el déficit de sedimento causado por las presas. La crecida de cinco años de período de retorno analizada transportó el 26% de la carga anual de sedimento en suspensión del río Ebro, uno de los ríos más caudalosos de la Península Ibérica. Este estudio demuestra que los pantanos de Oliana y Rialb tienen una gran influencia en el transporte de sedimento en suspensión en el río Segre y que esta influencia podría ser modificada para maximizar el tránsito de sedimentos reduciendo el déficit de sedimento aguas abajo.

Palabras clave: Cuenca del Segre, crecida, sedimento en suspensión, turbidez, embalses, retención.

1. Introduction

Rivers transfer sediment from their headwaters to sedimentation zones and, ultimately, to the sea (Williams and Wolman, 1984). Although bedload determines the shape and form of alluvial channels, in general terms, most of the load is transported in suspension (Webb *et al*., 1995). Fine sediment has crucial functions along the river ecosystem and the disruption of its transport has morphological, ecological and economical effects such as channel erosion, alterations of habitats, reservoir's siltation (Valero-Garcés *et al*., 1999; Avendaño *et al*., 2000; Vericat and Batalla, 2006). Human-built infrastructures located in river channels, especially reservoirs, have severe effects on suspended sediment transfer. Indeed, large reservoirs throughout the world trap 25-30% of it (Vörösmarty *et al*., 2003). Nevertheless, further research is required to better understand all the consequences of this disturbance on fluvial and coastal ecosystems.

Our knowledge of suspended sediment transfer and of its disruption by reservoirs is still limited. This limitation has two main causes: i) suspended sediment transport is highly variable both in time and space (e.g., Walling and Webb, 1989), and ii) suspended sediment transport occurs mostly during floods, which are difficult to monitor, both because their magnitude and their unpredictability in the long-term (Beven and Carling, 1989; Bal-

Table 1. Monthly rainfall in Oliana in 2008 compared to the average for the 1971-2000 period (Sources: Servei Meteorològic de Catalunya and AEMET).
Tabla 1. Precipitación mensual en Oliana en 2008 comparada con la media en el período 1971-2000 (Fuentes: Servei Meteorològic de Catalunya y AEMET).

		Rainfall (mm)				
Period	Rain gauge	January	February	March	April	May
1971-2000 (average)	EM62 (CHE)	43.6	24.8	39.3	64.6	80.1
2008	W5 (XEMA)	26.6	14.2	23.6	100.2	149.4

asch *et al*., 2007). Fine sediment trapping in reservoirs has usually been assessed at the annual or even longer time scales (Brune, 1953; Dendy, 1974; Kummu and Varis, 2007), and very few studies (for example, Vericat and Batalla, 2005) address the effects of reservoirs on suspended sediment transport during floods. The knowledge of suspended sediment dynamics in impounded rivers is necessary for a better understanding of the magnitude of the sediment deficit caused by dams and in order to design management actions as flushing flows (Vericat and Batalla, 2007).

Within this context, the objective of this study was to quantify the possible effects of the Oliana-Rialb dam system on the suspended sediment transport along the Segre River during a 5-yr recurrence interval flood registered in May 2008.

2. The River Segre and the May 2008 flood event

2.1. *The River Segre*

The River Segre is the main tributary of the Ebro. It drains a large segment of the Pyrenees and its basin is about 13,000 km^2. The mainstream is around 265 km long (Fig. 1) and its mean discharge at the lowermost reach is 100 $m^3 \cdot s^{-1}$. In its medium segment, there are two large reservoirs: Oliana and Rialb. Oliana (11 km long) was built in 1959 with an initial capacity of 100 hm^3. Rialb (18 km long) was commissioned in 2001 with a capacity of 400 hm^3. Oliana's dam is only 3 km upstream Rialb's reservoir tail; therefore, the two reservoirs act as a single one with an impounding capacity of 500 hm^3. The Oliana-Rialb system has modified the flood regime in the 77% of the Segre basin that lies downstream the dams. In the pre-regulated period, floods in the Segre River occurred mostly during springtime –related to snow melt– or autumn –related to weather fronts. In the last century, there have been three major floods in the basin: 1907, 1931 and 1982.

2.2. *The May 2008 flood event*

The studied flood occurred in May 2008, after one week of rains at the end of an unusually wet two-month period (Table 1), which had drenched the soil and triggered snow thaw. The rain lasted from 22nd to 28th May and was concentrated in the headwaters of the basin,

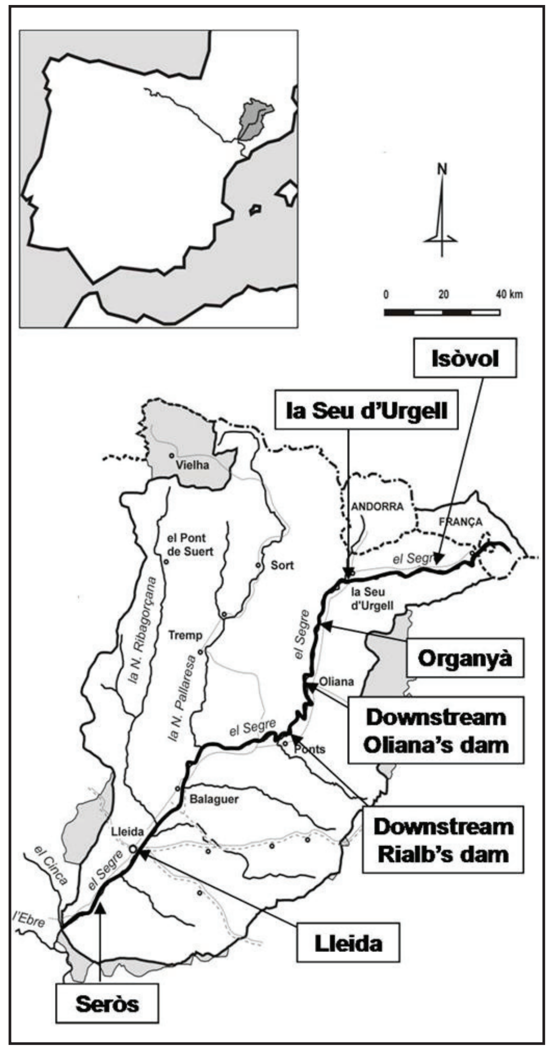

Figure 1. Location map of the Segre River basin (in grey) within the Iberian Peninsula in the context of the Ebro basin (a) and map of the Segre River basin (in white), highlighting the sampling sites (b).
Figura 1. Mapa de situación de la cuenca del río Segre (en gris) dentro de la Península Ibérica y en relación con el río Ebro (a) y mapa de la cuenca del río Segre (en blanco), en el que se destacan los siete puntos de muestreo (b).

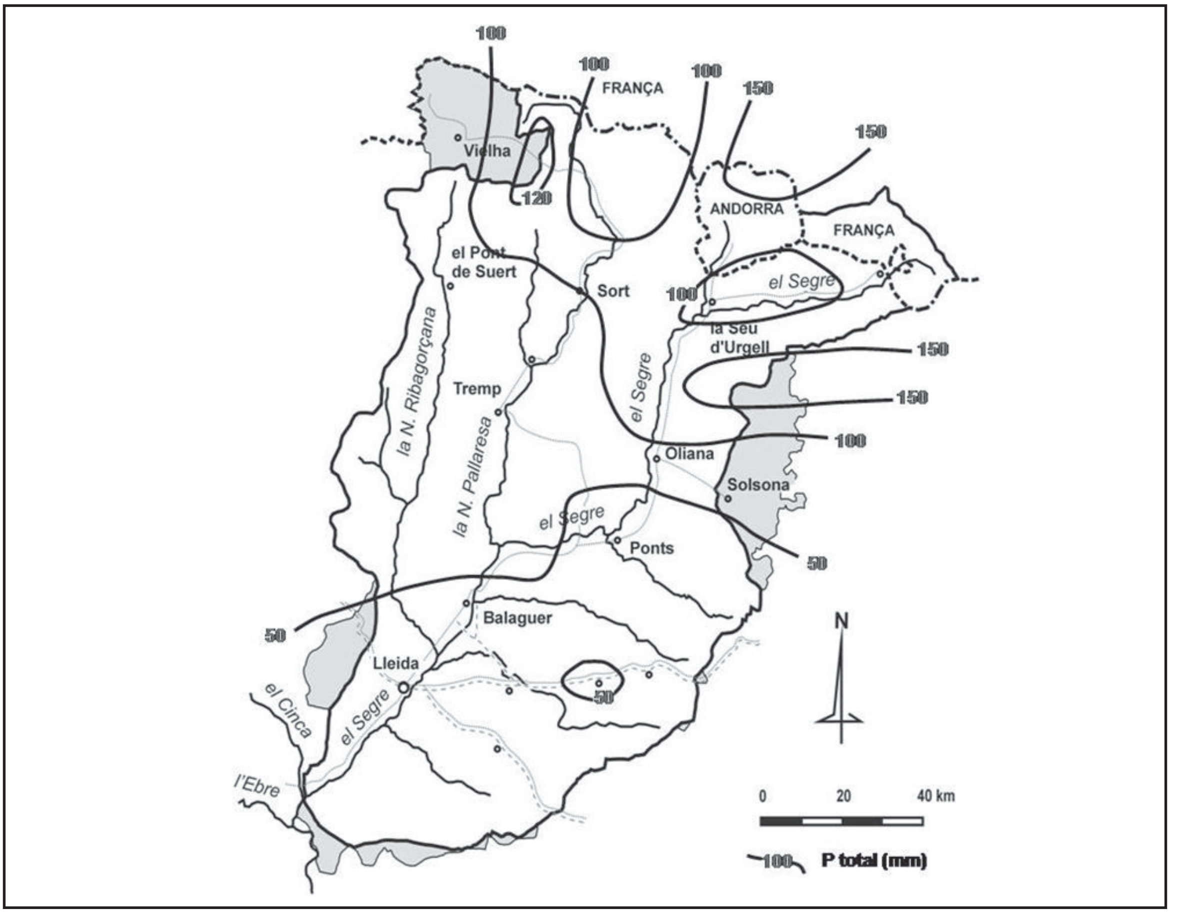

Figure 2. Map of isohyets of total rain (in mm) in the Segre River basin (in white) between 22nd and 28th May 2008 (from 39 rain gauges).
Figura 2. Mapa de isoyetas de precipitación total (en mm) en la cuenca del río Segre (en blanco) entre el 22 y el 28 de Mayo de 2008, elaborado a partir de los datos de 39 pluviómetros.

and more concretely, in the Eastern part of the Central Pyrenees (Fig. 2). The maximum rainfall measured in the basin occurred at Organyà (146 mm) and the area-averaged total rainfall was 72 mm.

The flood had a peak of 516 $m^3 \cdot s^{-1}$ at Organyà (EA111), the last gauging station before the Oliana-Rialb system, and of 776 $m^3 \cdot s^{-1}$ at Seròs (EA025). The May flood peak was about the 75% of the peaks registered in 1994 and 1997 and about only the 25% of 1982 flood peak (Fig. 3). According to the expected peak flows estimated by ACA (2002 and 2007), this flood had a return period of about five years (Table 2). The reservoirs system and the operations done to manage the incoming flood disrupted the flood downstream, in a manner that they could be considered two different hydrological events: a natural flood upstream the dams system and a man-made one downstream the dams. For instance, the hydrograph at Organyà, at the end of the non-regulated reach, has two peaks related to the temporal distribution of the rainfall in the headwaters of the basin (Fig. 4), whereas that of Balaguer, downstream the reservoirs system, shows five peaks (which also appear in the reconstructed hydrograph downstream Rialb's dam) corresponding to the way in which the dams commissioners managed the flood, opening and closing the sluicegates.

3. Methods

In order to calculate the suspended sediment transport along the Segre River during the May 2008 flood, suspended sediment concentrations were calculated at seven sites: Isòvol, La Seu d'Urgell, Organyà, downstream Oliana's dam, downstream Rialb's dam, Lleida and Seròs (Fig. 1 and Table 3).

Suspended sediment loads were calculated adding up the suspended solid discharge (Equation 1) during specific periods of time, which were chosen in order to allow coherent comparisons between the total suspended loads at each site.

$$SSL = 3.6 \cdot \sum_{i=1}^{n} q_i \cdot \Delta t_i \qquad (1)$$

where SSL (Mg) is the suspended sediment load that flowed through a site during the chosen time period; q_i (kg•s^{-1}) is the suspended sediment flux at time t=i; Δt_i is the data series' time step (1 h in our case); and n is the length in hours of the calculation period chosen. Suspended sediment flow was calculated according to:

$$q_i = 10^{-3} \cdot Q_i \cdot SSC_i \qquad (2)$$

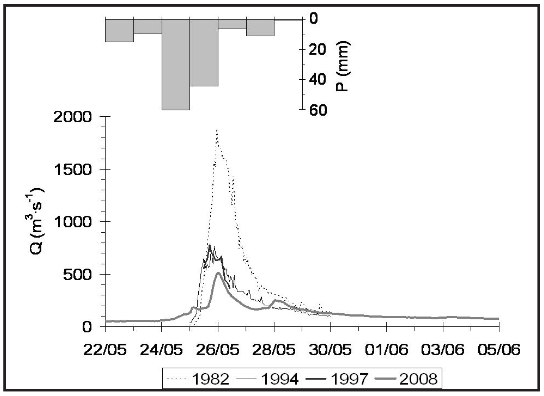

Figure 3. Event's hyetograph and hydrograph in Organyà (both in grey) compared to hydrographs of notable recent floods (Note: X-axis' values refer only to 2008's hyetograph and hydrograph).
Figura 3. Hietograma e hidrograma del episodio en Organyà (ambos en gris) comparados con los hidrogramas de avenidas recientes. Los valores del eje de abscisas sólo son válidos para el hietograma e hidrograma de 2008.

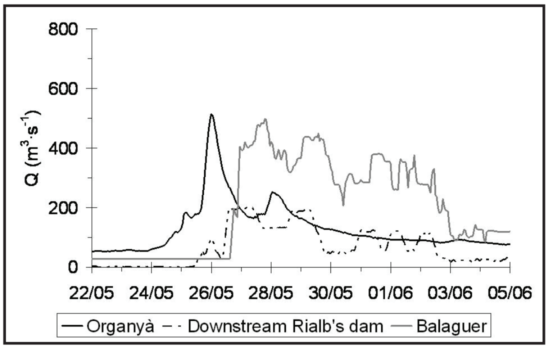

Figure 4. Hydrographs at Organyà (15 km upstream Oliana's dam), downstream from the Rialb Dam and in Balaguer (60 km downstream from Rialb Dam). (Data from Confederación Hidrográfica del Ebro).
Figura 4. Hidrogramas en Organyà (15 km aguas arriba de la presa de Oliana), aguas abajo de la presa de Rialb y en Balaguer (60 km aguas abajo de la presa de Rialb), elaborados a partir de datos de la Confederación Hidrográfica del Ebro.

where qi (kg•s^{-1}) is the suspended sediment flux at time t=i; Q_i (m^3•s^{-1}) is the water flow at time t=i and SSCi (mg•l^{-1}) is the suspended sediment concentration at time t=i.

According to Equations 1 and 2, hourly cotinuous flow and suspended sediment concentration data series per each site were required in order to calculate the suspended sediment flux at a given interval period and, ultimately, the suspended solid load at that interval. Methods used to obtain the aforementioned data series are discussed in the next sections.

3.1. *Water flow data*

Water flow data series consisted of gauging measures by the Ebro Water Authorities; however, in two cases –downstream Rialb's dam and in Lleida– due to the lack of gauging stations, this information had to be estimated. Water flow downstream Rialb's dam was calculated through Equation 3, assuming that there were no lateral water inputs between Oliana's and Rialb's dams (Fig. 1):

$$Q_{DownstreamRialb,i} = Q_{DownstreamOliana,i} - \frac{\Delta V_{Rialb,i}}{3600 \cdot \Delta t_i}$$

Table 2. Expected peak flows for several return periods at different points along the Segre basin, estimated from rainfall-discharge modelling (Source: ACA 2002(*) and ACA 2007(**)).
Tabla 2. Caudales pico esperados para diversos períodos de retorno en diferentes puntos de la cuenca del río Segre, calculados con modelos lluvia-escorrentía (Fuente: ACA 2002(*) y ACA 2007(**))

Site	Recorded peak flow during May 2008 flood ($m^3 \cdot s^{-1}$)	Return period (years) 5(*)	10(**)	25(*)
		Expected peak flow ($m^3 \cdot s^{-1}$)		
Organyà	516	553	766	1060
Balaguer	499	578	862	1281
Seròs	776	696	976	1474

where $Q_{Downstream\ Rialb,i}$ ($m^3 \cdot s^{-1}$) is the instantaneous water flow downstream Rialb's dam at time t=i, QDownstream Oliana,i ($m^3 \cdot s^{-1}$) is the instantaneous water flow downstream Oliana at time t=i, $\Delta V_{Rialb,i}$ (m^3) is the variation in the volume stored in Rialb's reservoir between time t_{i-1} and time t_i, and Δti (h) is the time elapsed between t_{i-1} and t_i.

The resulting series were trimmed of negative values (which were equalled to zero) and were afterwards smoothed through a five-component moving average. The resulting calculated hydrograph downstream Rialb's dam fairly matched in shape the one measured at Balaguer (Fig. 4). Similarly, water flow in Lleida was equalled to the one flowing through Balaguer (25 km upstream) three hours earlier assuming that lateral flow from tributaries was negligible, which is a plausible consideration because little rainfall was recorded in the lower third of the basin. All the assumptions in this method were supported by field observations.

3.2. *Suspended sediment concentration data*

Conversely, suspended sediment concentration (SSC) series had to be entirely calculated (they were not series of directly measured quantities). We obtained these series in two different ways: i) through water samples and, where available, ii) through turbidity records (Fig. 5).

3.2.1. Suspended sediment concentration from water samples

During the falling limb of the flood, between 27th and 30th May, several water samples were taken at each one of the seven sampling sites: Isòvol, La Seu d'Urgell, Organyà, downstream Oliana's dam, downstream Rialb's dam, Lleida and Seròs (Table 4). The samples were taken approximately at the axe of the river and in the surface of the water. Samples were vacuum-filtered through cellulose and glass microfibre filters (Millipore®, 0.045 mm pore size) in the lab. These filters were dried for 24 hours between two sheets of drying paper at room temperature and subsequently weighed to a milligram in a high-precision scale. Then, suspended sediment concentration was calculated as:

$$SSC = \frac{m}{V} \tag{4}$$

where SSC ($mg \cdot l^{-1}$) is the suspended sediment concentration, m (mg) is the mass of suspended sediment in the filtered volume, and V (l) is the filtered volume of water.

Finally, SSCs were used to fit statistical functions of these in relation to time (t, SSC) at each of the sampling sites. These functions were subsequently used to obtain a continuous hourly SSC series for each site. Since only interpolation was possible, the limits of the calculation period were the times of the first and the last samples (roughly, from 27th May to 30th May).

3.2.2. Suspended sediment concentration from turbidity data

Turbidity data series from automatic gauging stations were used to derive suspended sediment concentrations at those sections equipped with turbidimetres, i.e. downstream Rialb's dam, Lleida and Seròs. In these stations water turbidity is continuously measured every 10 seconds by means of a Hach SS6 turbidity probe. Averages of 15-minute time intervals are recorded in a logger.

Turbidity records require a calibration to be transformed to SSCs. Indeed, suspended sediment concentration series were obtained through ad hoc calculated calibration equations (Table 5). These equations were linear regression models fitted to data pairs composed of turbidity and suspended sediment concentration (T, SSC). It is worth to mention that, in the case of the sections downstream Rialb's dam and in Lleida, we measured the turbidity associated to thirteen lab-prepared samples; each of those samples had a known suspended sediment concentration, ranging from 12 to 4000 mg•l^{-1}. Conversely, at Seròs, the data came from twelve river water samples taken beside the turbidity gauging station between 10th May and 18th June 2008, their SSC ranging between 29 and 699 mg•l^{-1}.

Turbidity series at Lleida had a source of uncertainty deserving specific consideration. Turbidity was measured at a station in the Seròs Canal instead of the Segre River; thus, those data were not direct measures from river water but from a diversion canal's. Anyhow, we assumed that the turbidity at a given time in the Segre River was equal to that measured in the Seròs Canal gauging station, judging the two kilometres between the diversion and the turbidimetre not a long enough distance to significatively modify the suspended sediment concentration in the fast-moving water flowing along the canal.

Table 3. Data available at each sampling site

Tabla 3. Información disponible en cada punto de muestreo

Site	Water flow: Data availability	Water flow: Gauging station used	Suspended sediment: Number of samples	Suspended sediment: Sampling site	Turbidity: Data availability	Turbidity: Gauging station used
Isòvol	yes	A256	2	By the gauging station A256	no	---
La Seu d'Urgell	yes	A023	3	Just upstream Segre & Color rivers' junction	no	---
Organyà	yes	A111	3	From the Pont de Fígols (4 km upstream the tail of Oliana's reservoir)	no	---
Downstream Oliana's dam	yes	A083	3	From the catwalk just downstream Oliana's dam (300 m downstream the dam)	no	---
Downstream Rialb's dam	no[1]	A083 (+ E076 for stored volume)	3	From the bridge of C -1412b road (1.6 km downstream the dam)	yes	Q913 (5.8 km downstream Rialb's dam)
Lleida	no[2]	A096 (Balaguer)	3	From the Pont Nou (N-IIa road)	yes[3]	Q914 (Canal de Seròs)
Seròs	yes	A025	7	By the gauging A025	yes	Q941

[1] Discharge downstream from the Rialb Dam was estimated using Equation 3

[2] Discharge in Lleida was considered equal to that in Balaguer, with a three-hour delay (eg. QBalaguer(t=0 h) = QLleida(t=3 h))

[3] The turbidity gauging station used in Lleida is not located in the Segre River but in the Seròs Canal

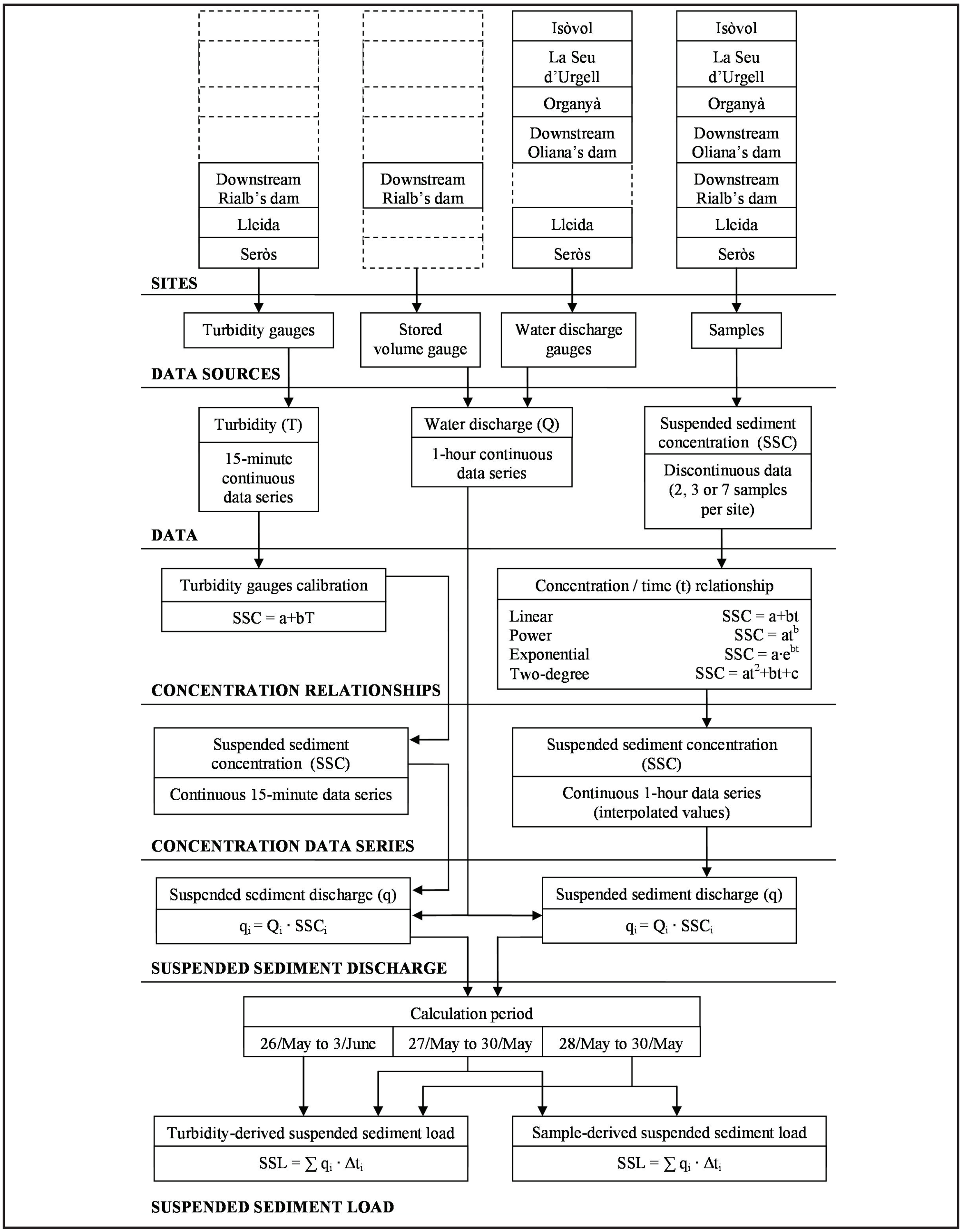

Figure 5. Methodological flow-chart for the estimation of the suspended sediment loads based on available data at each monitoring site.

Figura 5. Metodologías de cálculo de la carga de sedimento en suspensión usadas en función de la información disponible en cada punto de muestreo.

Table 4. Suspended sediment concentration (SSC) of all the samples* and comparison to turbidity-derived SSC.
Tabla 4. Concentración de sedimento en suspensión (SSC) de todas las muestras y su comparación (cuando es posible) con la SSC calculada a través de la turbidez.

Site	27/May			28/May			29/May			30/May		
	Sampling hour (UTC)	Sample-derived SSC	Turbidity (mg•l^{-1})	Sampling hour (UTC)	Sample derived	Turbidity SSC (mg•l^{-1})	Sampling hour (UTC)	Sample derived SSC	Turbidity (mg•l^{-1})	Sampling hour (UTC)	Sample derived SSC	Turbidity (mg•l^{-1})
Isòvol	---	---	---	18:10	283	---	---	---	---	16:10	103	---
La Seu d'Urgell	18:25	343	---	17:15	254	---	---	---	---	13:50	61	---
Organyà	16:45	535	---	16:15	459	---	---	---	---	13:10	168	---
Downstream Oliana's dam	16:20	249	---	14:20	156	---	---	---	---	12:40	79	---
Downstream Rialb's dam	15:40	8	142	13:30	11	48	---	---	---	12:10	46	373
Lleida(*)	11:30	390	1240	9:15	146	370	---	---	---	9:40	63	385
Seròs	11:15	699	705	11:00	195	82	18:30	199	261	14:30	84	75
	15:00	349	355	19:30	115	83	---	---	---	---	---	---
	20:45	428	257	---	---	---	---	---	---	---	---	---

(*) In Lleida, samples were taken from the Segre River and turbidity was measured in the Seròs Canal, diverted from the river 2 km upstream

Turbidity data series were continuous, hence, they could be used to quantify the suspended sediment dynamics in a much more accurate way than sedigraphs calculated from punctual water samples. Webb *et al*. (1997) have estimated the uncertainty of this procedure within the range of -57% to 29%.

3.3. *Limitations due to data scarcity*

Table 3 summarizes data availability at each site and highlights data limitation, which have been explained above. These main limitations were: the lack of water discharge data at the base of Rialb's dam and at Lleida; the scarce number of samples taken; the short sampling period compared to the flood duration; and the lack of continuous turbidity data at Lleida and at the four sites located upstream Rialb's dam. Note that, at Lleida, neither the flow data nor the turbidity data are *in situ*, direct measurements. These uncertainties forced us to work with some hypotheses, which should be taken into account in assessing the accuracy and reliability of the results. These hypotheses have been discussed above and are listed herein after: a) negligible lateral water supplies and no flow lamination between Oliana's and Rialb's dams; b) negligible lateral water supplies and no flow lamination between Balaguer and Lleida; c) negligible water withdrawals along the Segre River; and d) negligible variations in the suspended sediment concentration in the two first kilometres of the Seròs Canal.

4. Results and discussion

The Oliana-Rialb reservoirs system caused a disruption of the flood, which was therefore completely different in each one of the following three reaches: the one upstream the reservoirs system, the impounded reach itself (a 32-km-legth reservoir system) and the one downstream the reservoirs. Indeed, according

Table 5. Calibration equations of the three turbidity gauges
Tabla 5. Ecuaciones de calibración de los tres turbidímetros.

Site	Calibration equation	R^2 (%)	Turbidity range (NTU)	Suspended sediment concentration range (mg•l^{-1})
Downstream Rialb's dam	SSC = 6.41 T + 7.30	99.7	4-635	12-4000
Lleida	SSC = 7.38 T + 8.34 99.9		6-547	12-4000
Seròs *if T ≤ 6 NTU*	SSC = 1.54 T	77.4		
if 6 NTU < T <63 NTU	SSC = 1.76 T – 10.46	78.7	24-163	29-699
if T ≥ 63 NTU	SSC = 4.66 T – 54.25	80.2		

[1] Suspended sediment concentration (SSC) expressed in mg•l^{-1} and water turbidity (T) in NTU

to sample-derived results, between 27th and 30th May, in the first reach, the non-regulated one, suspended sediment load increased as moving downstream, along with suspended sediment concentration and water flow; in the second reach, the Oliana and Rialb reservoirs stopped almost all the suspended sediment (between 75% and 97%) and much of the water flow; and in the third reach, suspended sediment load increased again, along with suspended sediment concentration and water flow (Fig. 6 and Tables 6 and 7). Similarly, the turbidity readings show that suspended sediment concentration behaved differently in the three turbidity gauging stations: downstream Rialb's dam, there was a short pulse of suspended sediment concentration (700 mg•l^{-1}) followed by a long-lasting cloud, with a maximum of 500 mg•l^{-1} (Figure 7a); conversely, at Lleida the first short pulse (of 1,350 mg•l^{-1}) was followed by smaller pulses which roughly matched water flow variations (Figure 7b); finally, at Seròs, the first short pulse (of 1,140 mg•l^{-1}) was as well followed by smaller pulses, but of a higher frequency (Figure 7c), not related to water flow variations, but probably caused by suspended sediment dilution with clear water coming from the Utxesa dam, fed by the Seròs Canal.

4.1. *Dams effects on suspended sediment transport*

In the period from 27th May to 30th May, the Oliana-Rialb reservoirs system trapped between 75% (according to turbidity-derived results) and 97% (according to sample-derived results) of the incoming suspended sediment transport. The latter result, which we judged more reliable than the former, agrees with the 95% suspended sediment trapping efficiency in the large reservoirs of the lower Ebro River during two consecutive floods with return periods of 10 and 5 five years, respectively (Vericat and Batalla, 2005). Furthermore, these values agree as well with the 96% long-term trapping efficiency measured in Mequinensa-Riba-roja (Sánchez-Arcilla *et al*., 1998), a large reservoirs system in the Ebro River (1700 hm^3), and with the 95% long-term trapping efficiency of the Oliana-Rialb's system, calculated with empirical curves (Brune, 1953; Dendy, 1974) from the ratio between its storage capacity and annual inflow (i.e. 0.5).

However, if taken separately, the two reservoirs had different behaviours: Oliana reservoir captured about half of the incoming suspended sediment whereas Rialb reservoir stopped almost all of it. Both the differences in size between the two reservoirs and the differences in all-time stored sediment (related to time of service) could explain this, but it could be as well caused by the two dams being differently operated during the calculation period (Figure 6b and Table 6). Indeed, Oliana released all the water it received and some more to make room (119% of the total water that flowed through Organyà just 15 km upstream) whereas Rialb stored water (it only released 62% of the water volume that flowed out of Oliana).

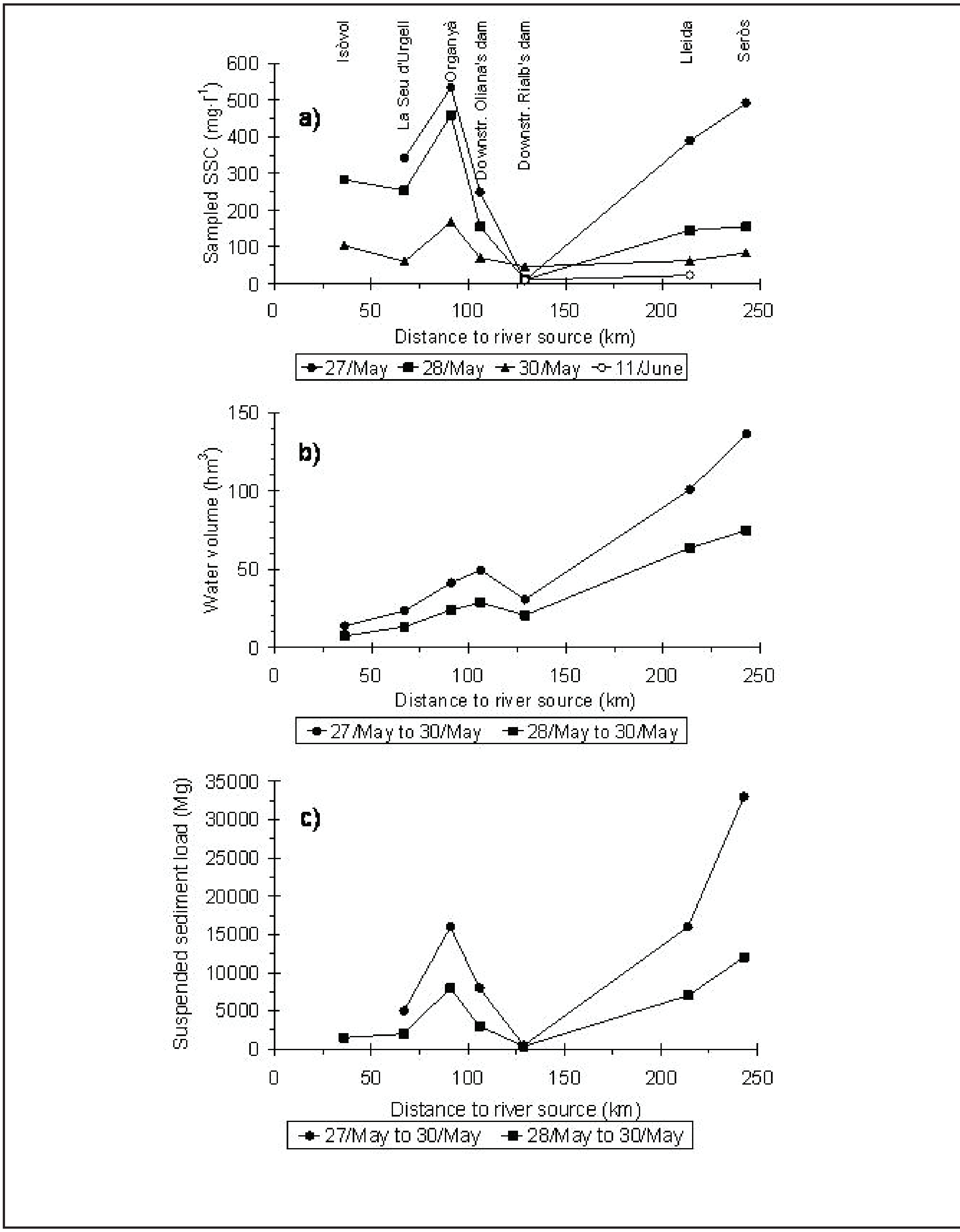

Figure 6. Sampled SCC at each site (a); water volume (b) and sample-derived suspended sediment load (c) transported through each site for two different calculation periods.

Figura 6. SCC medida en cada punto de muestreo (a); volumen de escorrentía (b) y carga de sedimento en suspensión calculada a partir de las muestras (c) que pasaron por cada punto de muestreo durante dos períodos de cálculo distintos.

Table 6. Sample-derived and turbidity-derived suspended sediment load that flowed through each studied site, rounded off to the closest thousand.
Tabla 6. Cargas de sedimento en suspensión en cada punto de muestreo calculadas a partir de las muestras y a partir de la turbidez, y redondeadas al millar.

	Calculation period							
Site	27/May to 30/May (3 days)			28/May to 30/May (2 days)			26/May to 3/June (8 days)	
	Water volume (hm^3)	Sample-derived suspended load (Mg)	Turbidity-derived suspended load (Mg)	Water volume (hm^3)	Sample-derived suspended load (Mg)	Turbidity-derived suspended load (Mg)	Water volume (hm^3)	Turbidity-derived sus load (Mg)
Isòvol	13.8	---	---	7.4	1,500	---	---	---
La Seu d'Urgell	23.4	5,000	---	13.3	2,000	---	---	---
Organyà	41.4	16,000	---	24.1	8,000	---	---	---
Dowstream Oliana's dam	49.4	8000	---	28.7	3,000	---	---	---
Downstream Rialb's dam	30.7	500	4,000	20.6	400	4,000	75.9	18,000
Lleida	101.0	16,000	52,000	63.6	7,000	30,000	215.9	98,000
Seròs	118.2	33,000	26,000	79.2	12,000	10,000	223.8	45,000

However, these results do not answer the following question: did the Oliana-Rialb reservoirs system really stop that quantity of suspended sediment or was it just that the sediment was still crossing the system at the time of our last sample being taken and thus it hadn't arrived to the downstream Rialb's sampling point yet?

Turbidity series help to address this question. The suspended sediment load for the 27-30 May period at the downstream Rialb calculated from the turbidity series was eight times bigger that the one calculated from the samples: 4,000 Mg and 500 Mg (Table 6). Then, if this proportion was conserved throughout the flood (and there is no evidence to dispel this hypothesis), the suspended sediment load for the 26 May-3 June period at the downstream Rialb sampling point calculated from the samples would have been 0.125 of the one actually calculated from the turbidity series, that is, 2,200 Mg and 18,000 Mg respectively.

We conclude that, of the 16,000 Mg of suspended sediment that flowed past Organyà between 27 and 30 May, only 2,200 Mg (or less than 14%) had flowed past downstream Rialb's dam sampling point until 3 June. In other words, we can be sure than at least 86% of the sediment transported by May 2008 flood was trapped in the reservoirs system.

If put in context, the sediment trapped in the Oliana reservoir in May 2008 was only 1% of its annual suspended sediment mean retention as estimated by Avendaño *et al*. (1997): 0.58 hm^3•year-1 in the period 1959-1985, or 780,000 Mg•year^{-1}. However, the implications of such a comparison are very limited because annual suspended sediment mean retention is an average of an extremely variable regime, which depends strongly on the occurrence of floods.

4.2. *Suspended sediment transport downstream the dams*

Suspended sediment load increased downstream Rialb's dam. Since the sediment was coming neither from upstream the Segre River nor from its tributaries downstream Rialb's dam (Noguera Pallaresa River did not supply a significant amount of it), it had to be coming mainly from the channel and floodplains; therefore, previously deposited sediment was being mobilized by the flood. This hypothesis is supported by Figure 7b, in which SSC matches well with water flow, that is, as water flow gets faster and higher, it has the competence to entrain in-channel and bank sediments, carrying more suspended sediment. Moreover, according to figures 7b and 7c, the first SSC peak was much higher than the following ones in both Lleida and Seròs. This behaviour has been as well observed in the Ebro River (Tena *et al*., 2011) and could be explained by the progressive depletion of in-channel and on-floodplain sediment throughout the flood: the first water flow peak mobilized most of it and it got scarcer and scarcer as secondary peaks flowed past.

Therefore, due to this in-channel sediment mobilization and in spite of the great amount of suspended sediment stopped by the dams, sample-derived suspended sediment load calculated at Seròs (33,000 Mg from 27th May to 30th May) was 26% of the total suspended sediment that flowed down the Ebro River at Móra d'Ebre in the hydrological year 2007-08 (Tena *et al*., 2011). We conclude that a modest five-year-return-period flood in the River Segre (16% of the Ebro's basin) transported in only three days (1% of the year) the 26% of the annual suspended sediment load at the lowermost Ebro.

4.3. *Reliability of the results*

As discussed in the methods section, data scarcity forced us to assume some work hypotheses that could have affected results' reliability in a non-quantifiable way. Hence, to be on the safe side, suspended sediment transport results should be seen as rough estimates, reliable only to the highest order of magnitude. Special care should be taken with Lleida's results for they had too many sources of uncertainty as discussed previously.

The clearest example of uncertainty in our results was the difference between sample-derived SSC and turbidity-derived SSC found downstream Rialb's dam and in Lleida. Indeed,

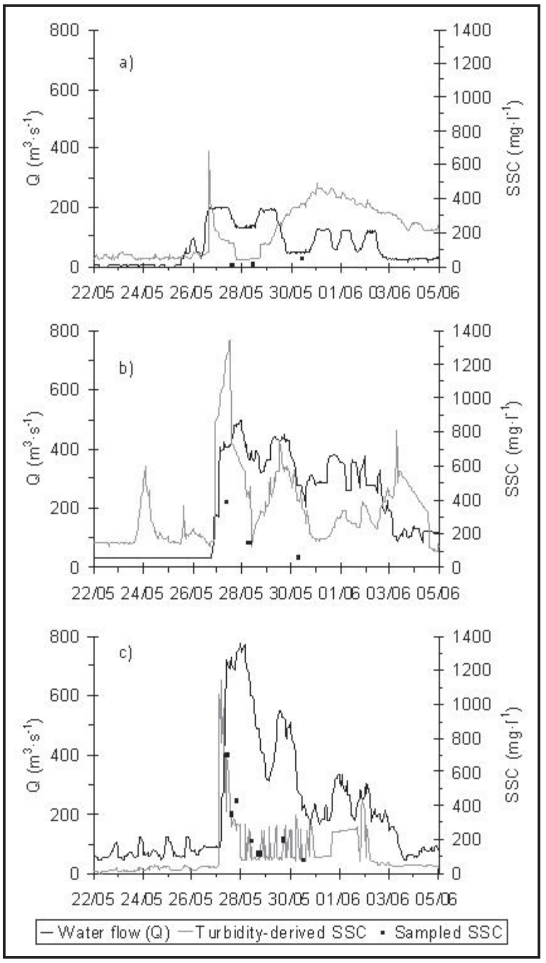

Figure 7. Temporal evolution of water flow and turbidity-derived suspended sediment concentration (SSC) downstream from the Rialb Dam (a), and further downstream in Lleida (b) and in Seròs (c).

Figura 7. Evolución temporal del caudal y de la concentración de sedimento en suspensión (SSC) calculada a partir de la turbidez aguas abajo de la presa de Rialb (a), en Lleida (b) y en Seròs (c).

sample-derived SSC was always smaller than turbidity-derived SSC (between 4 and 18 times smaller in Rialb, and between 3 and 6 times smaller in Lleida); conversely, in Seròs sample-derived SSC was between 0.4 and 1.3 times smaller than turbidity-derived SSC (Table 4).

T-SSC calibrations are statistically significant (R^2 of 99.7% and 99.9%, respectively; Table 5) although substantial differences have been obtained between the turbidity-based and water sample-based SSCs (as discussed above). Two reasons could explain these differences: i) the two turbidity probes were away from the water sampling sites (4 km downstream in Rialb's sampling site; and turbidity was obtained in the Seròs Canal instead of the Segre River, in the case of Lleida); and, ii) the way in which the automatic turbidimeter probes were operated (pumping water from the river and measuring through their pipes) could have had effects on the T readings. Furthermore, these two reasons could explain as well why sampled-derived SSC and turbidity-derived SSC matched well at Seròs: samples were taken in front of the turbidimetre and the calibration equations were calculated from river samples. However, this goodness of fit may be overestimated, the data set used to fit the calibration equations were not independent of the set of data those equations intended to predict (actually, five of the twelve data pairs used in the fitting were measured during the flood; therefore, it is logical that the five predicted SSC values match well the five measured SSC).

In summary, these results are providing an order of magnitude of the suspended sediment transport during a single event through a dam complex in a regulated river and, although the absolute values of some of the estimations could be discussed in terms of their uncertainties, general trends, dynamics and the shape of the sedigraphs in the downstream direction remain a valuable information not just to understand the sediment deficit caused by dams but also to give support to more sediment-friendly management plans.

5. Conclusions

A five-year-return-period flood occurred in May 2008 in the River Segre was sampled and monitored at different sections through its mainsteam in order to a) estimate the effects of the Oliana-Rialb dam complex on the suspended sediment dynamics and transport, and with the objective of b) assessing the sediment load passing the lowermost part of the basin and ultimately, being supplied to the main River Ebro upstream Ribaroja. Despite data uncertainty, our near basin scale approach provided the following final remarks and conclusions:

a) The Oliana-Rialb reservoir system stopped between 75% and 97% the suspended sedi-

Table 7. Percentage of suspended sediment stopped related to the suspended sediment that entered the Rialb Reservoir from 27/May to 30/May.
Tabla 7. Porcentaje de sedimento en suspensión retenido en relación con el sedimento en suspensión que entró en el embalse entre el 27 y el 30 de Mayo.

Reservoir	River reach	Suspended sediment retention (%) According to sample-derived results	According to turbidity-derived results
Oliana + Rialb reservoirs	Organyà –Downstream Rialb's dam	97	75 (1)
Oliana reservoir only	Organyà –Downstream Oliana's dam	50	---
Rialb reservoir only	Downstream Oliana's dam – Downstream Rialb's dam	94	---

(1) Turbidity-derived suspended load downstream Rialb's dam is compared to sample-derived suspended load at Organyà

ment that flowed into them.

b) Each reservoir had a slightly different trapping efficiency, probably due to a different flood management: Oliana let the water flow while Rialb stored water.

c) Downstream the dams system, suspended sediment transport increased again, due to in-channel and on-floodplain sediment re-mobilization, and, in four days, it amounted to one quarter of the annual suspended sediment load of the Ebro River's basin at Móra d'Ebre.

This study showed that this reservoirs system has a great influence in suspended sediment transfer along the Segre River and that this influence could be modified in some extent through dams' management; however, in order to confirm it, more research in different flood and dam's management scenarios should be conducted, with ad hoc measuring equipment.

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