Universitat de Lleida

Eco-geomorphological dynamics in contrasting Mediterranean rivers with different degrees of flow regulation

Gemma Lobera Galán

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Universitat de Lleida

Tesi Doctoral

ECO-GEOMORPHOLOGICAL DYNAMICS IN CONTRASTING MEDITERRANEAN RIVERS WITH DIFFERENT DEGREES OF FLOW REGULATION

GEMMA LOBERA GALÁN




Memòria presentada per optar al grau de
Doctor per la Universitat de Lleida
Programa de Doctorat en 0901 Ciència i Tecnologia Agrària i Alimentària

Directors:
Dr. Ramon J. Batalla
Dr. Damià Vericat

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Cover photos: River Ésera upstream of the Barasona reservoir (Up-left hand; Gemma Lobera Galán, 2011); River Ésera downstream of the Barasona reservoir (Down-left hand; Gemma Lobera Galán,2013); River Siurana upstream of the Siurana reservoir (Up-right hand; Gemma Lobera Galán, 2011); River Ésera downstream of the Siurana reservoir (Down-right hand; Gemma Lobera Galán, 2011).

Caminante, son tus huellas el camino y nada más;
Caminante, no hay camino, se hace camino al andar. Al andar se hace el camino, y al volver la vista atrás se ve la senda que nunca se ha de volver a pisar.

Antonio Machado

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Summary

The effects of dams on river flow regimes, sediment transport, channel morphology, bed mobility and macroinvertebrate communities were studied in Mediterranean rivers of the Iberian Peninsula at multiple temporal and spatial scales. First, a multiple spatial scale approach was designed to evaluate the long-term effects of regulation on river geomorphology. This study was conducted in four large basins: Llobregat, Ebro, Júcar and Guadalquivir, all representing distinct hydroclimatic regions and degrees of regulation. Results show that regulation changes their flow regimes, with a generalized reduction in flood magnitude and frequency. This, in addition to the decrease in downstream sediment supply, results in a reduction of active bars and vegetation encroachment (channel stabilization). Geomorphic stabilization limits river channel dynamics and may contribute to the environmental degradation of the fluvial ecosystem. Secondly, an assessment of water and sediment fluxes, bed disturbance and benthic invertebrate assemblages was conducted in two climatically-contrasting Mediterranean regulated rivers of the Ebro catchment (i.e. the Ésera and the Siurana). Floods were responsible for more than 90% of the suspended sediment load in the Siurana, while this percentage felt to 70% in the Ésera, indicating the importance of baseflows for sediment transport in this river. Suspended sediment concentrations up to 30 g l^{-1} were registered in the River Ésera. This phenomenon is related to the high sediment availability, with the Ésera acting as a non-supply-limited catchment due to the high productivity of the upstream badlands. In contrast, the Siurana is a supply-limited system due to its low geomorphic activity and reduced sediment availability, with suspended sediment concentrations remaining low, even during high magnitude events (maximum concentrations at 2.5 g l^{-1}). Reservoirs in both rivers trap up to 90% of the suspended load, although total runoff is only reduced in the Ésera. The Ésera shifts from a humid mountainous hydro-sedimentary regime to a semi-arid type of river downstream from the dam, in which most of the sediment load is associated with a few flood events (i.e. dam releases). In the upstream reaches, riverbed material is frequently entrained and morphological changes were observed following floods. Thus, the river channel experiences high dynamism. Downstream, topographical changes happened only once and were associated with the competent floods which occurred during the 2-year study period. In the Siurana, the reservoir exerts the opposite effect; the dam modified the Mediterranean flow regime of the river to a more permanent and stable regime typical of less-arid regions. Bed disturbance was notably reduced downstream from the reservoir, creating more uniform and less dynamic habitats. Altogether, damming causes significant differences in taxonomic composition of the benthic invertebrate communities in the Siurana, but the species richness remained almost the same. Density and biomass increased notably below the dam although diversity decreased. The thesis describes and quantifies changes on the bio-physical structure and functioning of the fluvial ecosystem in dammed Mediterranean rivers and provides comprehensive insights in the field of the Eco-Geomorphology.

Key words: Channel morphology, sediment transport, bed disturbance, benthic invertebrates, dams, flood regime, Mediterranean rivers.

Resum

Aquesta tesi analitza l'efecte de les preses sobre el règim de cabals, el transport de sediments, la mobilitat de la llera, i la comunitat de macroinvertebrats en rius Mediterranis de la Península Ibèrica a diferents escales espacio-temporals. En primer lloc, es va realitzar un estudi a gran escala per avaluar l'efecte a llarg termini de la regulació sobre la geomorfologia fluvial. L'estudi es va dur a terme a quatre grans conques: Llobregat, Ebre, Xúquer i Guadalquivir, representant regions hidroclimàtiques contrastades i diferents graus de regulació. Els resultats mostren que la regulació modifica el règim de cabals reduint la magnitud i la freqüència de les crescudes. Aquest fet, juntament amb la disminució de l'aportació de sediments des d'aigües amunt, produeix una pèrdua de barres sedimentaries i una intrusió de la vegetació causant una ràpida estabilització de la llera. Aquest procés limita el dinamisme del riu i pot contribuir a la degradació de l'ecosistema fluvial. En segon lloc, es va realitzar un anàlisi del flux d'aigua i sediments, la dinàmica de la llera i la resposta dels macroinvertebrats bentònics en dos rius regulats amb diferent grau de Mediterraneïtat de la conca de l'Ebre (l'Ésera i el Siurana). Les crescudes són responsables de més del 90% del transport de sediment en suspensió al Siurana, i a l'Ésera la proporció és redueix al 70% degut a la importància del cabal base. Aquest fenomen està relacionat amb l'elevada disponibilitat de sediment a la conca degut a l'alta productivitat de les àrees font (*badlands*). Durant les crescudes es van registrar concentracions màximes de gairebé 30 g l^{-1}. En canvi, el Siurana és un riu amb poca activitat geomorfològica i baixa disponibilitat de sediment. La concentració de sediment en suspensió es manté baixa, fins i tot durant crescudes d'alta magnitud (concentracions màximes de 2.5 g l^{-1}). En els dos casos, l'embassament reté fins el 90% de la càrrega de sediment en suspensió, però l'aportació hídrica només es redueix en el cas de l'Ésera. L'Ésera passa de tenir un règim hidro-sedimentari típic de rius de muntanya a tenir un règim de riu intermitent aigües avall, amb la major part de la càrrega sedimentària transportada durant pocs episodis de crescuda (soltes de la presa). En el tram d'aigües amunt, les partícules de la llera són mobilitzades de forma freqüent i s'observen canvis morfològics després de cada crescuda. És a dir, el tram presenta un elevat dinamisme. Aigües avall només es van observar canvis topogràfics a la llera un sol cop, associats amb la única crescuda que va tenir lloc durant el dos anys d'estudi. Al Siurana, la presa exerceix l'efecte contrari, canviant el règim altament variable característic de zones Mediterrànies a un règim més permanent i estable típic de regions menys àrides. La pertorbació de la llera es redueix molt aigües avall, creant un hàbitat més uniforme i menys dinàmic. En el cas del Siurana aquests canvis causen diferències notables en la composició taxonòmica dels macroinvertebrats, encara que la riquesa d'espècies es manté intacte. La densitat i la biomassa augmenten aigües avall però la biodiversitat disminueix. La tesi descriu i quantifica canvis en l'estructura bio-física i el funcionament de l'ecosistema fluvial en rius Mediterranis regulats i proporciona informació inèdita fins ara en el camp de la Eco-Geomorfologia.

Paraules clau: Morfologia fluvial, transport de sediments, preses, règim de cabal, macroinvertebrats, rius Mediterranis.

Resumen

Esta tesis analiza el efecto de las presas sobre el régimen de caudales, el transporte de sedimentos, la morfología y la movilidad del cauce, y la comunidad de macroinvertebrados en ríos Mediterráneos de la Península Ibérica a diferentes escalas espacio-temporales. En primer lugar, se llevó a cabo un estudio a gran escala para evaluar el efecto a largo plazo de la regulación en la geomorfología fluvial. Este estudio se realizó en cuatro grandes cuencas: Llobregat, Ebro, Júcar y Guadalquivir, que representan varias regiones hidro-climáticas y grado de regulación. Los resultados muestran una reducción generalizada de la magnitud y la frecuencia de las crecidas. Este hecho, junto con la reducción del suministro de sedimentos, produce una pérdida de barras activas y una intrusión de la vegetación, estabilizando el cauce fluvial. La estabilización limita el dinamismo del lecho del río y puede contribuir a la degradación del ecosistema fluvial. En segundo lugar, se analizó el flujo de agua y sedimentos, la dinámica del cauce y la respuesta de los macroinvertebrados en dos ríos regulados con diferente grado de Mediterraneidad de la cuenca del Ebro (Ésera y Siurana). Más del 90% del transporte de sedimentos en suspensión en el Siurana sucede durante crecidas, mientras que se reduce al 70% en el Ésera debido al papel del caudal de base en la carga sólida del río. Este fenómeno está relacionado con la alta disponibilidad de sedimentos en la cuenca y la alta productividad de las áreas fuentes (*badlands*). Durante crecidas se registraron concentraciones de hasta 30 g l^{-1}. En cambio, el Siurana es un río con poca actividad geomorfológica y poca disponibilidad de sedimentos. La concentración de sedimentos en suspensión se mantiene baja, incluso durante crecidas (valores máximos de 2.5 g l^{-1}). En ambos casos, el embalse retiene hasta el 90% de la carga de sedimentos en suspensión, aunque la aportación hídrica solo se reduce en el Ésera. El Ésera es un río con un régimen hidro-sedimentario característico de zonas de montaña, que se transforma aguas abajo en un régimen de tipo intermitente propio de zonas semiáridas, con la mayor parte de la carga sedimentaria transportada durante pocos episodios de crecida (sueltas de la presa). Aguas arriba, las partículas del lecho son movilizadas frecuentemente y se observan cambios morfológicos después de cada crecida. Es decir, el tramo presenta un elevado dinamismo. Aguas abajo, solo se observaron cambios topográficos en el cauce una vez, asociados al único episodio que tuvo lugar durante los dos años de estudio. En el Siurana, la presa ejerce el efecto contrario, cambiando el régimen de caudales característico de zonas Mediterráneas a un régimen más permanente y estable típico de regiones menos áridas. La perturbación del lecho se ve reducida notablemente, creando un hábitat más uniforme y menos dinámico. Todos estos cambios provocan diferencias significativas en la composición taxonómica de los macroinvertebrados en el Siurana, aunque la riqueza de especies se mantiene prácticamente intacta. Por otro lado, la densidad y la biomasa aumentan aguas abajo pero la biodiversidad disminuye. La tesis describe y cuantifica cambios en la estructura bio-física y el funcionamiento del ecosistema fluvial en ríos Mediterráneos regulados y proporciona información inédita en el campo de la Eco-Geomorfología.

Palabras clave: Morfología fluvial, transporte de sedimentos, presas, régimen de caudales, macroinvertebrados, ríos Mediterráneos.

Chapter 1

1. INTRODUCTION

1. 1. Transfer of water and sediments in fluvial systems

Rivers are complex and dynamic systems that transfer water and sediments continuously in space, from the production or erosion zones (as per Schumm, 1977), through the transfer zones (e.g. channel networks) to, ultimately, deposition zones such as floodplains, estuaries and deltas. Although in perennial systems the transfer of water occurs continuously on time, sediment transport occurs intermittently as dictated by thresholds that are ultimately controlled by the availability and characteristics of the sediments, channel morphology and flow hydraulics. Milliman and Syvitsiki (1992) estimated a mean annual global land-ocean sediment flux of ca. 20×10^{9} t year $^{-1}$. More recently, Vanmaercke et al. (2011) assessed catchment sediment yields (SY) in Europe, and found that both Mediterranean and Mountain regions have generally the highest SY due to a combination of factors that include climate, topography, lithology and land use. However, spatial and temporal variability is very high and predicting catchment sediment yield is still one of the main challenges in geomorphic research (de Vente et al., 2006). For instance, Batalla and Vericat (2011) found that the SY in the northern catchment of the Ebro basin is five times higher than that in the southern part. They attributed this difference to the distinct hydrological and geomorphic behavior of the regions. Furthermore, the temporal variability of sediment transport in Mediterranean regions is very high, with a high intra-annual and inter-annual variability (e.g. López-Tarazón et al., 2009; Buendía et al., 2014; De Girolamo et al., 2015).

The sediment loads of many rivers are largely influenced by human activity. Farnstworth and Milliman (2003) estimated that the human activity may be directly or indirectly responsible for 80-90% of the fluvial sediment delivered to the oceans. Land use change such as clearance of natural vegetation generally increase soil erosion (Morgan, 1986; Walling and Fang, 2003) and, conversely, the urban development and afforestation tend to reduce sediment production in headwaters and, consequently, the SY in the outcomes of the catchments (Nadal-Romero et al., 2012; Buendia et al., 2015). In-channel gravel mining has been shown to alter sediment transport dynamics and channel morphology (e.g. Bobrovitskaya et al, 1996; Kondolf, 1997). The increase or decrease of precipitation due to climate change also affects sediment transport. For instance, Mou (1996) reported that a decrease of the annual precipitation in the River Yellow caused a marked reduction of the annual sediment load. Finally, reservoir construction is probably the most important influence on land-ocean sediment fluxes, resulting in a remarkable reduction of sediment load (Walling and Fang, 2003). Worldwide, more than 45,000 large dams (i.e. above 15 m high) trap around 25-30% of the total land to ocean sediment flux (between 4×10^9 and 5×10^9 t $year^{-1}$; Vörosmarty et al., 2003) and 15% of the world's total annual river runoff (>65,000 km^3; Nilsson et al., 2005). Consequently, dams interrupt the continuity of sediment transport and cause changes on downstream channel morphology and sedimentology, ecological impacts in downstream sections and, ultimately, increase the risk of erosion in deltas and coastal environments (e.g. Meade and Parker, 1985; Vörosmarty et al., 2003; Vericat and Batalla, 2006; Walling, 2006). However, downstream adjustments can vary in time due to so-called relaxation periods (i.e. period between the dam closure and the establishment of a new state of equilibrium). Adjustments can be rapid in semi-arid regions but they can extend to millennia at other regions (Petts and Gurnell, 2005).

1. 2. Mediterranean rivers: variability and impacts

The Mediterranean climate is characterized by a high seasonality rainfall and temperatures, with hot and dry summers and cold and wet winters (Gasith and Resh, 1999). Such climate is present in five different areas of the world: the Mediterranean Basin, coastal California, central Chile, the Cape region of South Africa, and the southwest and southern parts of Australia (for a complete characterization of the environment in the Mediterranean regions see Conacher and Sala, 1998). Mean annual precipitation usually ranges from 275 to >1000 mm, with rainfall mainly in winters although in some regions (e.g. the Mediterranean Basin) rainfall often occurs in spring and autumn (Aschman, 1973; Miller, 1983). Mediterranean rivers are subjected to sequential hydrological disturbances of flooding and drying over an annual cycle, which is seasonally predictable but can vary in intensity and duration from year-to-year (Gasith and Resh, 1999; Hershkovitz and Gasith, 2013). Mediterranean rivers are also marked by a notable altitudinal gradient between the headwaters and the outlet, hence different flow conditions can be found with and between Mediterranean regions. Streams located in high elevated areas (i.e. mean annual rainfall >1000 mm) are characterized by a bimodal pattern in the flow regime, with highest discharge following the onset of rain and following snowmelt in spring (e.g. Sabater et al., 1992), but maintaining a permanent flow throughout the year. In contrast, rivers located in semi-arid areas (i.e. mean annual rainfall <500 mm), show a less permanent flow regime (ephemeral regimes in some cases). The effects of the seasonal hydrological variability on freshwater organisms and their adaptations in Mediterranean rivers have been reported widely in the literature, often involving adaptive strategies to avoid or to recover from droughts or floods (e.g. Gasith and Resh, 1999; Bonada et al., 2007a, b; Bonada and Resh, 2013; Robson et al., 2013; Hershkovitz and Gasith, 2013). For example, aquatic invertebrates have evolved traits such as small and large sizes, short life cycle duration, resistance forms to drought and aerial active dissemination (Bonada et al., 2007a, b). Natural disturbances pose an evolutionary pressure that make these systems ecologically unique, with a high level of endemism and perhaps among the most vulnerable to environmental damage from human activities (Gasith and Resh, 1999; Bonada and Resh, 2013).

In Mediterranean regions water availability and demand are most of the time out-of-phase; furthermore, demand is likely to increase in the near future. As a result, Mediterranean rivers have been heavily impounded, hosting over 3,500 large dams for water storage, hydropower production, irrigation, navigation and flood control (Cuttelod et al., 2008). In particular, Spain has more than 1200 large dams in operation, more than any other country in Europe (Batalla, 2003; Batalla et al., 2004). Dams have a hydrological and geomorphological effect along the river system, changing its character and functioning (e.g. Kondolf, 1997; Hauer and Lorang, 2004; Grantham et al., 2013). The hydrological alterations below dams include changes in flow variability at multiple temporal scales, shift in the timing and magnitude of floods, and disruption to seasonal patterns (e.g. Ward and Stanford, 1979, 1995; Petts, 1984; Ligon et al., 1995; Batalla et al., 2004). In particular, regulated Mediterranean rivers show a reduction in the magnitude and frequency of high flow events, and a complete inversion of natural seasonal flow patterns due to releases for irrigation during the summer (i.e. the dry season flows) (Batalla et al., 2004; Theodore et al., 2013). Furthermore, all the bedload and most of the suspended load is trapped in the reservoir, as well as all the sediment-associated contaminants (e.g. Vericat and Batalla, 2006; Tzoraky et al., 2007; Meybeck et al., 2007). The effects of the impoundment on downstream reaches are controlled by sediment availability and supply, and the magnitude of the released flows. If the water released from a dam still has competence to entrain bed material it becomes *hungry water* (as per Kondolf,1997). The main consequences are river bed degradation, especially by channel narrowing, coarsening of bed sediments and channel bed incision (e.g. Liébault and Piégay, 2001; Simon and Rinaldi, 2006; Vericat et al., 2006). Downstream, these effects can be compensated by sediment supply from tributaries. However, if the water released from dams does not have enough competence to transport the sediments supplied from tributaries or other local sources (e.g. bank collapse), channel aggradation may occur, with the reduction of flood conveyance and direct effects on habitat availability (Zahar et al., 2008). In addition, the decrease in flood magnitude and the increase in base flows in some seasons might promote vegetation encroachment, leading to the stabilization of the active channel, limiting river morphodynamics and increasing the magnitude of the deficit of sediment by stabilizing active areas (Sabaté et al., 2012; Nelson et al., 2013; Tuset et al., 2015). All these impacts on flow, sediment transport and associated processes contribute to the environmental degradation of the fluvial ecosystem (Ollero, 2010; Magdaleno et al., 2012), reducing the habitat for aquatic and riparian wildlife (Graf, 2006). For instance, in the case of the Lower Ebro Basin, changes on flow and flood regimes, the excess of nutrients, changes in water turbidity and the decrease of bed disturbances are the main factors controlling the rapid rate of macrophyte growth in the channel and their associated environmental effects (e.g. black-fly plague; Palau et al., 2004; Batalla and Vericat, 2009).

1. 3. Bed disturbance and macroinvertebrate communities

Erosion and sedimentation processes through the channel network control channel form and, consequently, the structure and functioning of the fluvial ecosystem. Channel morphology (slope, channel geometry and planform) is influenced by the interaction between water and sediments. Over long-term temporal scales, channel morphology remains in a quasi-equilibrium state (Williams and Wolman, 1984). Erosion, transport and sedimentation mainly occur during competent flood events. Sediments can be transported in suspension (i.e. fine sediments such as clay, silt or fine sands) or as bedload by rolling, sliding and saltating (i.e. mainly coarse sands and gravels).

Flood events are also one of the principal forces structuring stream macroinvertebrates communities, influencing on their distribution, composition and abundance and their eco-evolutionary adaptations (Lytle, 2002; Lytle and Poof, 2004; Death, 2008). Their effect depends on the timing, duration, frequency, intensity and predictability of periods of high flow (Lake, 2000). Floods affect bed stability (i.e. entrainment, transport and deposition of sediments), and result in displacement and death of macroinvertebrates and their food sources (Townsend et al., 1997; Matthaei et al., 1999; Gibbins et al., 2007; Schwendel et al., 2011). Nevertheless, despite death is an obvious consequence, there still remains little empirical evidence of the percentage of drifters which actually suffer mortality. Intermediate levels of bed disturbance tend to stimulate biodiversity by maintaining environmental gradients and associated habitat complexity in both time and space (Arscott et al, 2000). However, extreme floods alter habitat structure dramatically and produce what is termed *catastrophic drift*; hence most of the benthic biota may be lost from the bed and transported downstream involuntary (i.e. Brittain and Eikeland, 1988). This phenomenon is an important reset mechanism in fluvial ecosystems, bringing biological communities to initial successional states, favoring different types of species over those that dominate during periods of stability (White and Picket, 1985; Grimm and Fisher, 1989; Power et al., 2013). Therefore, the impact of high-discharges on stream invertebrates depends on the degree of physical disturbance and habitat alteration it produces.

As an example, Gibbins et al. (2005) showed that sediment mobility contributed significantly to drift of *Baetis* mayflies; moreover, Robinson (2012) reported for macroinvertebrate drift that two peaks of fauna concentration were experienced during a large flood, the first associated with the increase of shear stress and the second (greater than the first) with the increase of sediment mobility, whereas just one peak was observed during small floods. These results are consistent with those reported by some other authors as Statzner et al. (1984) and Gibbins et al., (2007).

Hydrological alterations acts as an environmental filter, and so species have acquired resistance and resilience adaptations to persist in disturbed fluvial systems, including morphological, behavioral and life-history strategies to cope with their effects (Death, 2008). Townsend et al. (1997) reported that more flood-disturbed communities in New Zealand have high amounts of species with traits such as small size, high adult mobility, habitat generalist, clinger and flattened. In Mediterranean rivers, seasonality is a determining issue for invertebrate community structure, with typically lentic species (e.g. Heteroptera, Coleoptera and Odonata) dominant in summer and rheophilic species (i.e. Ephemeroptera, Plecoptera, and Trichoptera) dominant in wet periods (Rieradevall et al., 1999; Muñoz, 2003; Bonada et al., 2007a). Furthermore, Mediterranean species must possess specific adaptive mechanisms to survive or recover after drought and flood events; that systems also have high share of endemic species (Bonada and Resh, 2013). Mediterranean rivers are under a great deal of human stress (e.g. river regulation) with many species threatened and more vulnerable to extinction than biota inhabiting streams in more stable climate regions (Filipe et al, 2012). However, the most significant threat to biodiversity and ecosystem function is the physical habitat alteration, related to river regulation (Allan and Castillo, 2007). As aforementioned, dams reduce the sediment load and mostly flood magnitude, creating, in most of the cases, more uniform and less dynamic habitats downstream (Bunn and Arthington, 2002). These changes impact the macroinvertebrate communities (e.g. low diversity, shift assemblage from lotic to lentic species, increase abundance; Petts, 1984; Allan and Castillo, 2007), but also disrupted fish migration and loss of spawning gravels (Kondolf, 1997), increase the primary production (Petts, 1984) and increase riparian vegetation abundance but decrease their diversity (Gordon and Meentemeyer, 2006).

Studies on the effects of impoundments on macroinvertebrate communities in Mediterranean region are scarce. Prat (1981) and Puig et al. (1987) reported the influence of the reservoirs on the river Ter (Catalonia), where macroinvertebrate composition was affected by the impoundment but diversity was not. They attributed these results to the lack of thermal stress and the high substrate diversity availability. In the Kleinplaas dam (South Africa; Bredenhand et al., 2009), macroinvertebrate diversity was highly reduced below the dam, especially species of Ephemeroptera, Plecoptera and Trichoptera, being the diversity and abundance dropped to almost zero. In this case, the dam caused an increase of the water temperature due to a reduction of both the input water flow and the canopy cover. Cauzobon and Giudicelli (1999) studied the effects of the great reduction of the residual flow in the regulated Durance river. The main environmental consequences were the high annual thermal amplitude of the water and the reduction of the diversity of available habitats, thus causing a reduction of both the diversity and the density of the benthic communities (i.e. algae and macroinvertebrates). Conversely, hydropower dams tend to increase flow variability (at daily or sub-daily fluctuations) and tend to affect negatively the aquatic species (Grantham et al., 2013). As an example, hydropower generation produced high summer flow fluctuations in the River Cinca (Iberian Peninsula) that reduced the abundance and diversity of the benthic macroinvertebrates (García de Jalón et al., 1988).

2. AIM, OBJECTIVES AND STRUCTURE OF THE THESIS

The aim of this thesis is to assess the effects of dams on channel geomorphology, sediment transport, bed mobility and macroinvertebrate communities in selected Mediterranean rivers of the Iberian Peninsula. The selected rivers have different hydrological regimes and represent contrasted geomorphic conditions. This study integrates multiple temporal and spatial scale analyses built on four specific objectives (Fig. 1):

Objective 1*: To evaluate the effects of regulation on the river-channel geomorphology in four large catchments at multiple spatial scales.*

Objective 2*: To analyses water and sediment fluxes upstream and downstream from dams in two Mediterranean rivers with different degrees of Mediterraneity;*

Objective 3: *To evaluate bed disturbance patterns upstream and downstream from dams in two Mediterranean rivers with different degrees of Mediterraneity; and*

Objective 4: *To assess invertebrate community responses to river regulation and bed disturbance in a Mediterranean river.*

The following are the main hypotheses that are considered in the thesis:

H1. River regulation alters the hydrogeomorphic status of fluvial systems and causes channel stabilization and environmental degradation of the fluvial ecosystem in Mediterranean rivers;

H2. Dams interrupt the transfer of water and sediment, changing sediment transport dynamics, decreasing sediment loads and altering channel morphology. The magnitude of these effects will be controlled not just by the characteristics of the dams but also by the degree of Mediterraneity of the catchment; and

H3. Change in bed disturbance caused by regulation affects the macroinvertebrate communities.

Fig. 1 shows the interaction between each objective and the spatial and temporal extent of these. The thesis is presented as a series of papers following the regulations of the University of Lleida (Article 28 of the *Normativa acadèmica de doctorat de la Universitat de Lleida*). Note that, for this reason, each chapter has its independent figure and table numbering, and reference list. A list of figures and tables in each chapter is provided at the beginning of the document. Chapter 1 contains a general literature review while general details of the study catchments and methods are provided in Chapter 2. It is worth mentioning that specific details of the study areas and methods are presented in each of the papers in relation to the aim of these. Therefore, Chapter 2 only provides a general overview. The specific objectives are addressed from Chapters 3 to 6. The objective of each chapter is briefly introduced at the beginning, providing the general context of the paper and its status on the date this thesis was prepared. Therefore, a total of 4 papers are included in this document i.e. 3 published, 1 accepted (Fig. 1). Chapter 7 presents the general discussion and conclusions of the thesis, integrating the findings of each publication and in relation to the general aim of the thesis. Finally, several annexes are included containing relevant information obtained during the thesis. Amongst them we present one paper and one book chapter that were undertaken simultaneously to the thesis work and that help i) to contextualize the hydrosedimentary dynamics of the River Ésera and ii) to provide a more extended description of the interaction between sediments and macroinvertebrates in the River Siurana.

This thesis has been carried out within the background of the research project SCARCE Consolider Ingenio 2010 CSD2009-00065: *Assessing and predicting effects on water quantity and quality in Iberian rivers caused by global change.* The main aim of this project was to *describe and predict the relevance of global change impacts on water availability, water quality and ecosystem services in Mediterranean river basins of the Iberian Peninsula, as well as their impacts on the human society and economy* (Barceló, 2009). To achieve this aim four catchments in Spain were selected as case studies: Llobregat, Ebro, Júcar and Guadalquivir, which include a wide range of spatial, ecological and socio-economic scenarios. The project was structured in 10 Work Packages (WP). The thesis was undertaken within the framework of the WP3. The main goal of WP3 was analyze sediment transport and channel morphosedimentary dynamics of selected rives reaches from the micro to the mesoscale (meters to hundreds of m to km), with the objective to assess fish and invertebrate habitat suitability, and to forecast future evolution at the light of global change trends and scenarios. Field data obtained during this thesis (e.g. flow regime, grain size distribution, sediment transport and channel topography) was the basis to perform and calibrate the hydraulic models, habitat suitability models and hydrological and sediment transport models with different scenarios of climate change.

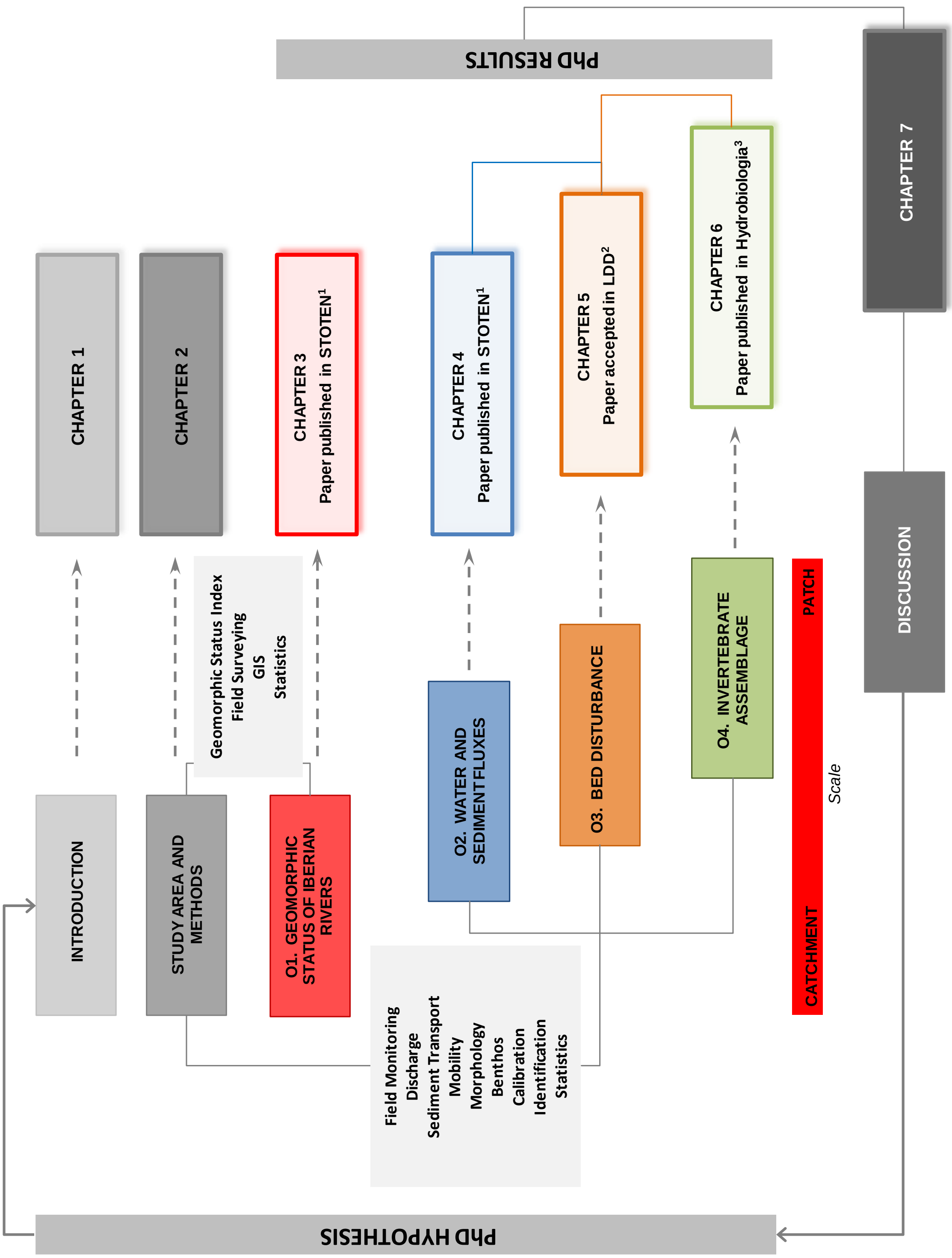

Figure 1. *Scheme of the thesis showing the main objectives, their interaction and the temporal and spatial extent of each, the chapters of the thesis and the associated papers.[1]: Science of the Total Environment (Impact factor: 3.976); [2]: Land Degradation and Development (Impact factor: 8.145); [3]: Hydrobiologia (Impact factor: 2.051).*

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Chapter 2

1. THE STUDY AREA

This thesis integrates multiple temporal and spatial scale analyses. Therefore, the study area does not encompass a single catchment; instead different sections at multiple catchments were selected. In the following sections we present first a general description of the study areas selected to assess the geomorphological status of four large Mediterranean basins in the Iberian Peninsula: Llobregat, Ebro, Júcar and Guadalquivir (Chapter 3). Finally, we introduce the general characteristics of the two meso-scale Mediterranean catchments used to study geomorphic processes upstream and downstream from dams and to assess how river regulation affects the ecological functioning of these rivers (Chapters 4, 5 and 6). The specific details of all study reaches are presented in the correspondent manuscripts; here we add additional general details of these.

1.1. Large Mediterranean basins

The Iberian Peninsula encompasses an extensive altitudinal, thermal, rainfall and hydrological gradient. The Peninsula can be divided into three different climate zones based on mean annual rainfall: i) semi-desert areas (0-300 mm y^{-1}), small and constrained to the southeast; ii) arid areas (300-800 mm y^{-1}), the largest zones and includes the Meseta, Ebro and Guadalquivir depressions as well as the Mediterranean area; and iii) humid areas (>800 mm y^{-1}), including both the north and many mountain ranges in the Peninsula (Castro et al., 2005; Sabater et al., 2009). Rainfall is also characterized by its high interannual variability, especially in the arid and semi-desert areas (i.e. the highest variability is observed in the Segura and Guadalquivir basins; Sabater et al., 2009). Mediterranean rivers are characterized by marked hydrological fluctuations, from low discharge during summer to flashy flood events in spring and autumn.

The Iberian Peninsula has a long history of human influence on water ecosystems. Water scarcity and irregular flow regimes have resulted in the construction of dams and canals, resulting in the regulation of many rivers (Sabater et al., 2009). Moreover, water demand is likely to increase in the near future, greatest in the Mediterranean coastal zone (Collins et al., 2009; Lorenzo-Lacruz et al., 2010). There are more than 1,200 reservoirs in the Iberian Peninsula, with a total storage capacity over 56,500 hm^3

(MAAM, Ministerio de Agricultura, Alimentación y Medio Ambiente; Lorenzo-Lacruz et al., 2012), which is almost the mean annual streamflow (i.e. 55,850 hm^3) of the 8 major rivers (Duero, Tajo, Guadiana, Guadalquivir, Segura, Júcar, Ebro and Miño) of the Iberian Peninsula (Lorenzo-Lacruz et al., 2012). Most of the dams were built during the second half of the 20th Century. None of the major dams were built for flood control, but the sheer volume of the impoundments would likely affect the flood magnitude (Batalla et al., 2004). Diverted water is used mainly for hydropower production and for irrigation. Results of MIMAM (2000b) show that only tributaries in the headwaters still have natural flow regimes, whereas discharge on these present a decreasing trend related, for instance, to changes in land cover (Gallart and Llorens, 2004). The Southern Pyrenees and other mountain areas in Spain, formerly used for marginal agriculture and grazing, have been abandoned since the middle 20th Century, resulting in the development and densification of forest cover (Lasanta, 1990). It is well known that an increase of the forest cover in a catchment implies a decrease in runoff (e.g. Beguería et al., 2003; Gallart and Llorens, 2003, 2004; Buendia et al., 2015). This change is attributed to the existing difference in evapotranspiration between forest and grass. Overall, these changes drive a reduction of around 20% of water resources observed in different basins along the Pyrenees (Gallart and Llorens 2004; García-Ruiz et al., 2008; Buendia et al., 2016).

A total of 74 river reaches of four Mediterranean catchments were selected to study their geomorphological status in relation to river regulation (Fig. 1, table 1): Ebro (85,530 km^2), Guadalquivir (57,527 km^2), Llobregat (4,923 km^2) and Júcar (21, 632 km^2).

Table 1.
General characterization of the study catchments in the Iberian Penninsula. See Figure 1 for their location.

	Ebro	**Guadalquivir**	**Júcar**	**Llobregat**	**Ésera**	**Siurana**
Catchment area (km^2)	85,534	57,527	21,632	4,923	1,500	610
Mean catchment elevation (m)	780	570	800	650	1,300	500
Mean annual precipitation (mm)	600	588	500	700	1,069	500
Max precipitation	3,500	1,600	1,500	1,800	2,500	700
Min precipitation	90	120	160	130	420	400
Mean annual runoff (hm^3)	14,000	7,739	986	487	770	44*
Land use (% of catchment)						
Artificial surfaces	0.9	1.1	0.9	5.2	0.1	0.1
Agricultural areas	47.4	62.9	47.5	38.4	15	49
Forests and semi-natural areas	51	33.6	48.1	55.8	84	49
Wetlands	0.1	0.6	0.0	0.0	0	0
Water bodies	0.6	1.8	3.4	0.5	0.3	1.4
Number of dams	187	118	19	3	1	3
Impoundment Ratio	0.6	1	2.2	0.46	0.15	0.6

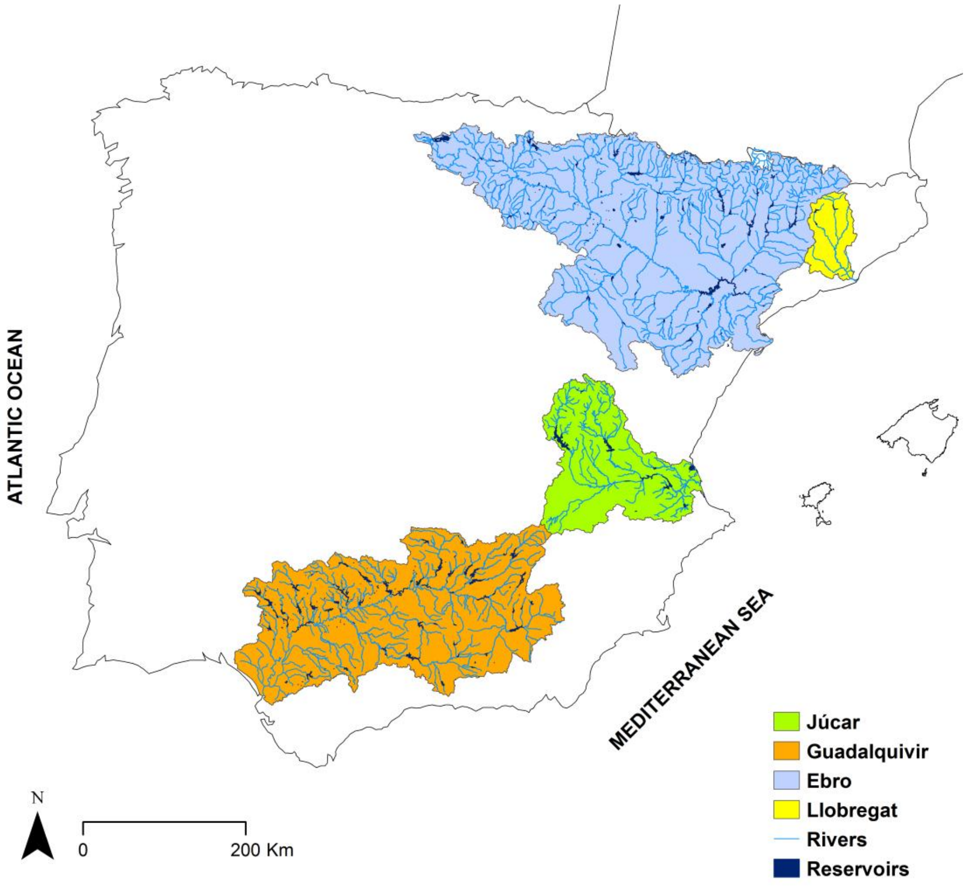

Figure 1. *The Iberian Peninsula with location of the study catchments (Júcar, Guadalquivir, Ebro and Llobregat), and their drainage network and reservoirs.*

1. 1. 1. The Ebro catchment

The Ebro is the largest Iberian river flowing into the Mediterranean Sea, draining an area of ca. 85,500 km^2 (Fig. 2). The River's headwaters are at Peñalara (Cantabria, 1980 masl) and the river flows 910 km from the Cantabrian Mountains to the Mediterranean Sea at the Ebro delta, one of the most important wetlands of the western Mediterranean. The main tributaries are: the Segre (ca. 13,033 km^2), Cinca (ca. 9,806 km^2), Jalón (ca. 8,630 km^2), Aragón (ca. 8,590 km^2), and Gállego (ca. 4000 km^2). Land uses have changed mainly in the second part of the century. Forest cover increased due to both abandonment and afforestation (Gallart and Llorens, 2004). Climatically, the basin belongs to the continental Mediterranean domain in most of the area, whereas it becomes semi-arid in the center of the Ebro depression. Mean annual precipitation is 600 mm, ranging from 3000 mm y^{-1} in the Pyrenees to <300 mm y^{-1} in the central plain. Mean annual runoff is 13,810 hm^3 for the 1912-2012 period at the lowermost part of the catchment (Tortosa gauging station), which corresponds to a mean annual discharge of 438 $m^{-3}s^{-1}$. Highest runoff was 30,821 hm^3 y^{-1} (1914-1915), whereas the minimum was 4,284 hm^3 y^{-1} (1989-1990). The mean annual flow in the last 50 years at Tortosa shows a decrease of 40% that has been attributed to the decrease in precipitation, increase in water consumption for irrigation and an increase of forest cover in the headwaters (MIMAM, 2000a; Gallart and Llorens, 2002).

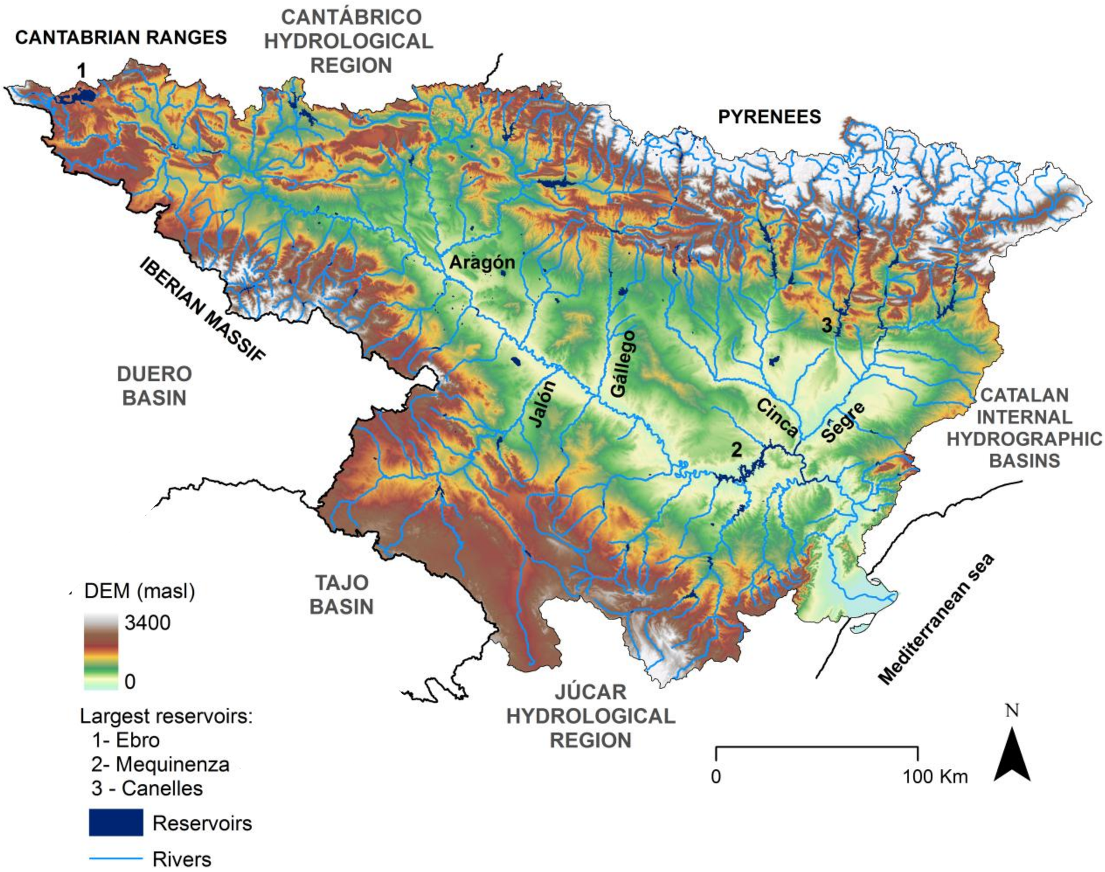

Figure 2. *Digital Elevation Model (DEM), drainage network and largest reservoirs of the Ebro basin.*

The Ebro is regulated by a total of 187 reservoirs. These impound 0.6 times (60% of) the mean annual runoff (reservoir storage volume is around 8,022 hm^3). The three largest impoundments are the Ebro Dam (540 hm^3, in operated since 1945) and Mequinenza Dam (1,534 hm^3, 1966), at the upstream and downstream ends of the River Ebro, respectively, and the Canelles Dam (678 hm^3, 1960) in the Noguera Ribagorçana River. In the lowermost part of the catchment, hydrological and geomorphological (especially sediment transport) alterations caused by the Mequinenza-Ribarroja-Flix Dam Complex (altogether impounding 1,752 hm^3 of water) has been extensively studied by several authors (e.g. Guillén and Palanques, 1992; Sanz et al., 1999; Roura, 2004; Vericat and Batalla, 2006; Vericat et al., 2006; Tena et al., 2011; Tena and Batalla, 2013). These studies have pointed out that around 90% of the suspended sediment load and 100% of bedload is trapped by these dams (Vericat and Batalla, 2006), but sediment load increases gradually in a downstream direction due to fine sediment supply from the main channel (erosion) and from tributaries (Tena and Batalla, 2013).

1. 1. 2. The Guadalquivir catchment

The River Guadalquivir is 657 km long and drains an area of about 57,527 km^2 (Fig. 3). The catchment is bounded by the Sierra Morena range in the north, the Baetic range in the south, and the Atlantic Ocean in the southwest. The headwaters of the Guadalquivir are located in the Canada de las Fuentes in the Cazorla mountain range (1,350 masl), passes through Córdoba and Sevilla and ends in the Atlantic Ocean by the city of Sanlúcar de Barrameda. The lowlands at the river's end are called *Marismas del Guadalquivir* with Doñana National Park to the west, where the river divides into several channels and forms a marsh environment. Most important tributaries of the Guadalquivir River are: i) on the true left hand: Guadiana menor, Guadalbullon, Genil, Corbones and Guadiara; ii) on the true right hand: Guadalimar, Jándula, Yeguas, Guadiato, Bembézar, Rivera de Huelva and Guadiamar. The floodplains of most of these rivers have been transformed into agricultural fields (such as rice fields and orchards), which lateral arms, meanders and wetlands have been channelized or drained (Sabater et al., 2009). The Guadalquivir basin is characterized by Mediterranean climate with mild temperatures (annual mean: 16 ºC) and irregular precipitation (mean: 588 mm y^{-1}). The rainfall is highly variable, both on inter- and intra-annual scales (with dry summers and precipitation mainly in late autumn and early winter). Furthermore, the rainfall is concentrated in a very short time period (less than 25% of the days of the year register precipitation).

Mean annual runoff near the outlet of the basin is 7,739 hm^3 y^{-1} (for the period 1941-2005, CEDEX) and the total water demands are of around 4,000 hm^3 y^{-1}, mainly for irrigation (87%). The basin is largely regulated, affecting the main river and all large tributaries. There are 118 reservoirs in the basin (water storage of 8,192 hm^3), 11 of which have a capacity greater than 200 hm^3. The largest ones are: Iznajar (981 hm^3), Breña II (823 hm^3), Negratín (567 hm^3), Tranco de Beas (498 hm^3) and Giribaile (475 hm^3). Lorenzo-Lacruz et al. (2012) showed a trend of decreasing annual streamflow in Guadalquivir basin, most likely related to a reduction in precipitation, influenced by the persistent positive of the North Atlantic Oscillation (NAO), together with the reforestation and the increasing water demand (i.e. population growth and irrigation demand; Lorenzo-Lacruz et al., 2012). However, this pattern is often reversed in summer in highly regulated rivers because of the large releases to supply water demand for irrigation and human consumption (e.g. downstream Tranco de Beas reservoir; Lorenzo-Lacruz et al., 2012). These low-flows (i.e. which will likely increase in the near future) are related with an increase of pesticide concentrations, generating higher levels in water and accumulation in sediments in the Guadalquivir basin (Masia et al., 2013).

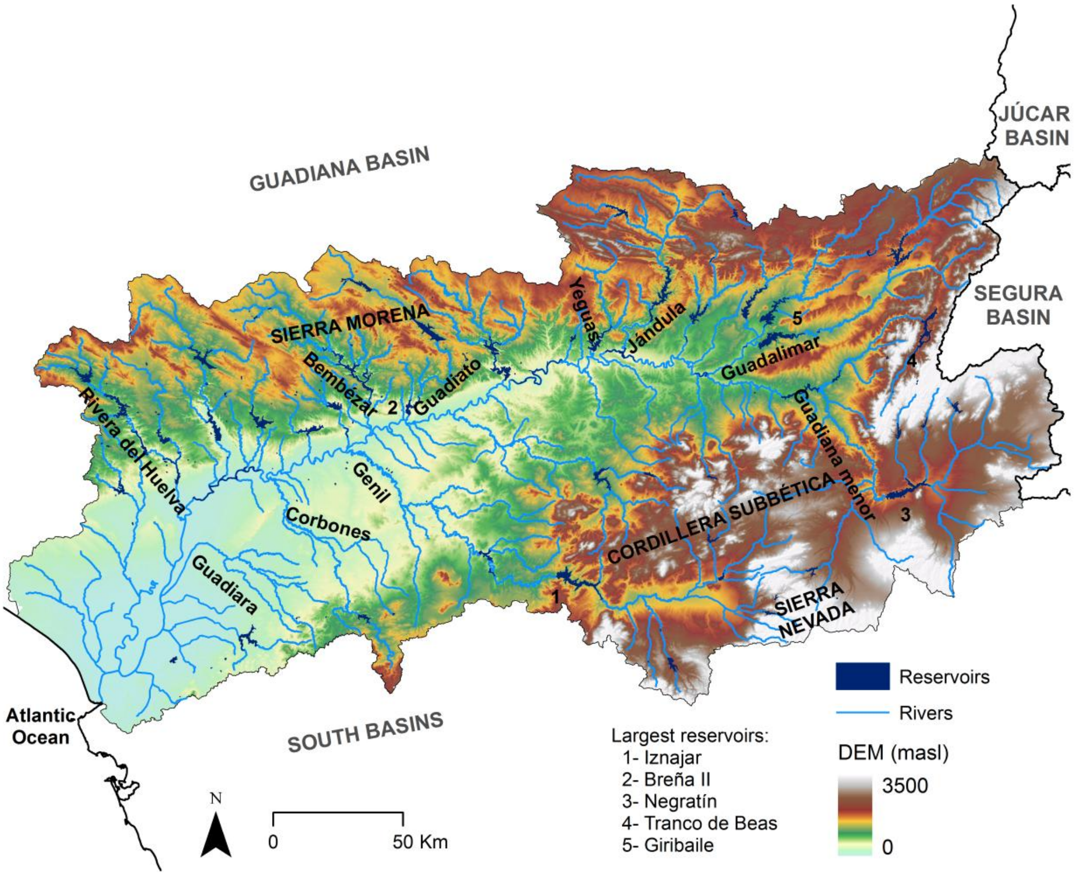

Figure 3. *Digital Elevation Model (DEM), drainage network and largest reservoirs of the Guadalquivir basin.*

1. 1. 3. The Llobregat catchment

The River Llobregat is 165 km long and drains an area of 4,923 km^2 (Fig. 4). The river originates in the pristine Easter Pyrenees, whereas it is soon affected by polluted waters from industrial effluents and sewage plants. In the lower part it flows through one of the most densely populated areas of the Mediterranean region (Barcelona Metropolitan Area). The Llobregat was considered one of the most polluted and degraded rivers in Western Europe, and the overexploitation of the underground water led to salinization of the aquifer, rendering 30% unusable (Marcé et al., 2012). It has two main tributaries: the Cardener (ca. 1,411 km^2) and Anoia (ca. 905 km^2) rivers. After the mid-20th century, land abandonment occurred in the basin (i.e. abandonment of agricultural and forest-related activities; Gallart et al., 2011; Delgado, 2011). Nowadays, the river basin is mainly occupied by forests and semi-natural areas (56%) and by agriculture (38%; analysis based on Corine Land Cover, 2006). Climatically, the basin belongs to the Mediterranean domain, with the main rainy seasons in spring and autumn. Mean annual precipitation is around 700 mm y^{-1}, ranging from 1800 in the Pyrenees to 130 mm y^{-1} (1950-2010). Snow seldom occurs in the headwaters although the low precipitation during winter and the mild temperatures mean the role of snowmelt on the hydrological regime is rather low (Gallart et al., 2011). Mean annual runoff is 487 hm^3 (1967-2011 in Sant Joan Despí gauging station near the outlet of the basin). Highest annual runoff is 1,500 hm^3 y^{-1} (1996), whereas the minimum was 124 hm^3 y^{-1} (2005), what shows a strong inter-annual variability.

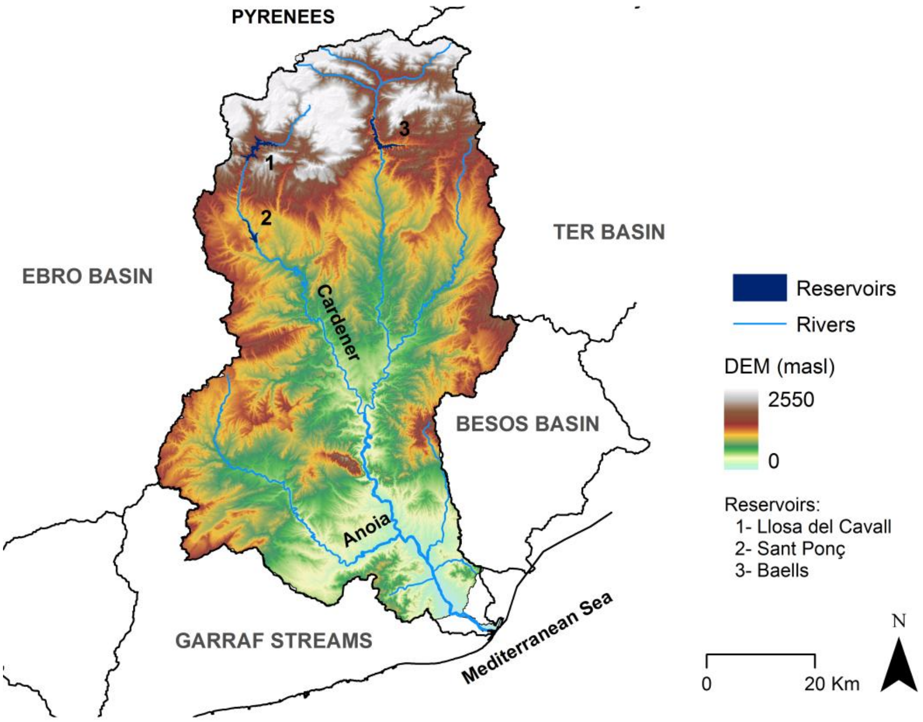

Figure 4. *Digital Elevation Model (DEM), drainage network and reservoirs of the Llobregat basin.*

Three large reservoirs were built in upstream sections of the Cardener and Llobregat rivers mainly for the water supply scheme of the Barcelona Metropolitan Area, impounding 0.46 times the mean annual runoff. The first dam to be built was Sant Ponç (12 hm^3) in 1954, in the River Cardener, followed by the Baells (118 hm^3, operated since 1979) in the River Llobregat and the Llosa del Cavall in the Cardener (80 hm^3, 1997). Runoff in the Llobregat and Anoia rivers showed significant decreasing trends between 1% and 3% per year for the period 1945-2005, specially during spring months, probably reflecting alterations in snow cover in the Pyrenees (Lorenzo-Lacruz et al., 2012). In contrast, Gallart et al. (2011) have shown an annual decrease of about 0.25%

of the mean annual sources related with an increase in forest cover in the headwaters. Sediment production in badland landscapes of the Vallcebre area (headwaters of the River Llobregat) has been extensively studied (e.g. Gallart et al., 2002; Regüés and Gallart 2004; Martínez-Carreras et al., 2007; Gallart et al., 2013). Just for a general definition, a badland is an area of unconsolidated sediment or poorly consolidated bedrock with little or no vegetation, which is useless for agriculture because of the intensely dissected landscape (Gallart et al., 2002). Liquete et al. (2009) estimated a Suspended Sediment Yield (SSY) in the River Llobregat of 19.8 t km^{-2} y^{-1}. The same authors classified this cathmnet in the medium category of suspended sediment concentration (<500 mg l^{-1}), following the classification scheme of Meybeck et al. (2003).

1. 1. 4. The Júcar catchment

The Júcar is the second largest river in the Iberian Peninsula Mediterranean region, with area of 21,632 km^2 (Fig. 5). The river runs for 512 km from the Montes Universales (1,700 masl), through the Mancha plateau and finally to the Mediterranean Sea. The dominant land use is forest (and semi-natural uses; 48%) and agriculture (47%). The coastal plain supports the majority of the agricultural irrigated production of the Júcar, and it is also characterized by the fact that more than 80% of the total population lives on its shore strip (Estrela et al., 2004). The River Cabriel is the largest tributary of the River Júcar, with a river length of 262 km and a catchment area of 4,690 km^2. Mean annual temperature is 13.6 ºC, while mean precipitation is 500 mm (1950-2010; ranging from 300 mm the driest years to 800 mm in the most humid ones). Mean annual precipitation presents a strong spatial variability, ranging from 160 mm y^{-1} in the south to 1,500 mm y^{-1} in the north of the basin. High intensity and short duration events may occur during autumn, most likely during October and November. In some coastal areas, the maximum rainfall recorded in one day is almost the mean annual rainfall, having a great effect in flooding and soil erosion. Particularly, in October 1982, an extremely heavy rainfall caused the Tous dam to break down and had an estimated peak flow of about 8,500 m^3 s^{-1}, with devastating effects downstream (MIMAM, 1998). According to different climate scenarios for the period 2010-2040 (released by the Spanish Agency of Meteorology (AEMET) in 2008), mean annual rainfall may decrease by 20% (Chirivella Osma et al., 2014).

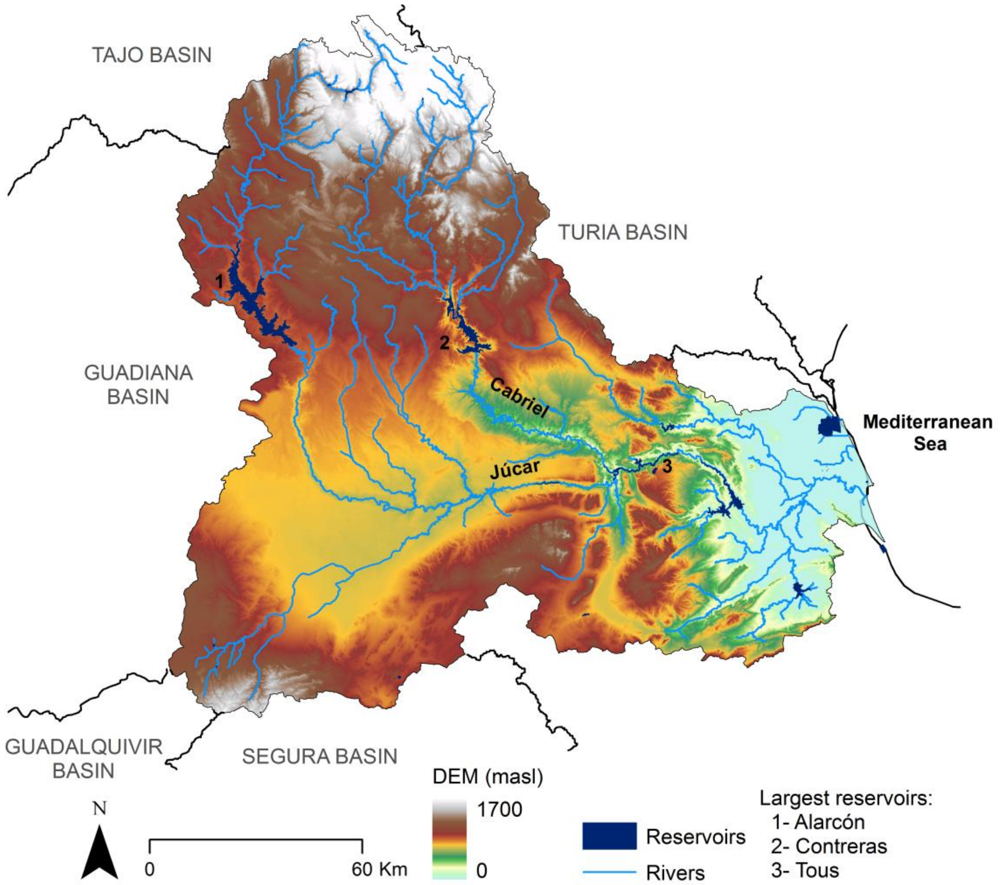

***Figure 5**. Digital Elevation Model (DEM), drainage network and largest reservoirs of the Júcar basin.*

Mean annual runoff is 986 hm^3 y^{-1} for the period 1946-2011 (Huerto Mulet gauging station, downstream from Tous Dam near the outlet). Highest runoff was 1,800 hm^3 y^{-1} in 1965 (no data available for 1982), whereas the minimum was 280 hm^3 y^{-1} in 2006. Mean annual discharge is 31 m^3s^{-1}, with a maximum in winter attributed to hydroelectric demands (Gil Olcina, 2006). Minimum discharge is registered in summer. Total water demands are around 3,230 hm^3, mainly for irrigation (79%). The Júcar and Cabriel rivers are strongly regulated, only the upper parts and short watercourses are not or little regulated. There are 19 reservoirs in the basin, with small dams for irrigation also distributed along the drainage network**.** Alarcón Dam (1,114 hm^3, operated since 1970), Contreras Dam (874 hm^3, 1974) and Tous Dam (340 hm^3, 1994) are the largest dams in the basin. The Júcar basin had a significant reduction of annual and seasonal streamflow in most of the gauging stations analyzed by Lorenzo-Lacruz et al. (2012). There are few studies related with sediment transport in the Júcar basin. For instance, Avendaño et al. (1997) studied the specific sediment yield (SSY) in 8 reservoirs (Embarcaderos, María Cristina, Benageber, Arquillo de San Blas, Buseo, Forata, Argos, Contreras, Beniarrés) along the basin. Results indicated an annual load of between 17 and 357 t km^{-2} y^{-1}, a high variability related to the speciffic characteristics of the basins (including climatology) that control sediment availability and supply to the river channels.

1. 2. Meso-scale Mediterranean basins

1. 2. 1. The River Ésera

Location and general characteristics

The Ésera is a mesoscale mountainous catchment (ca. 1,500 km^2) located in the Southern Central Pyrenees. It is the second largest tributary of the River Cinca, which in turn is the second main tributary of the Ebro basin (Fig. 6). The River Ésera is impounded by the Barasona Reservoir that is located near the outlet of the river. The River Isábena is the main tributary of the River Ésera, drains an area of 445 km^2 and flows into the River Ésera a few hundred meters upstream from the Barasona Reservoir.

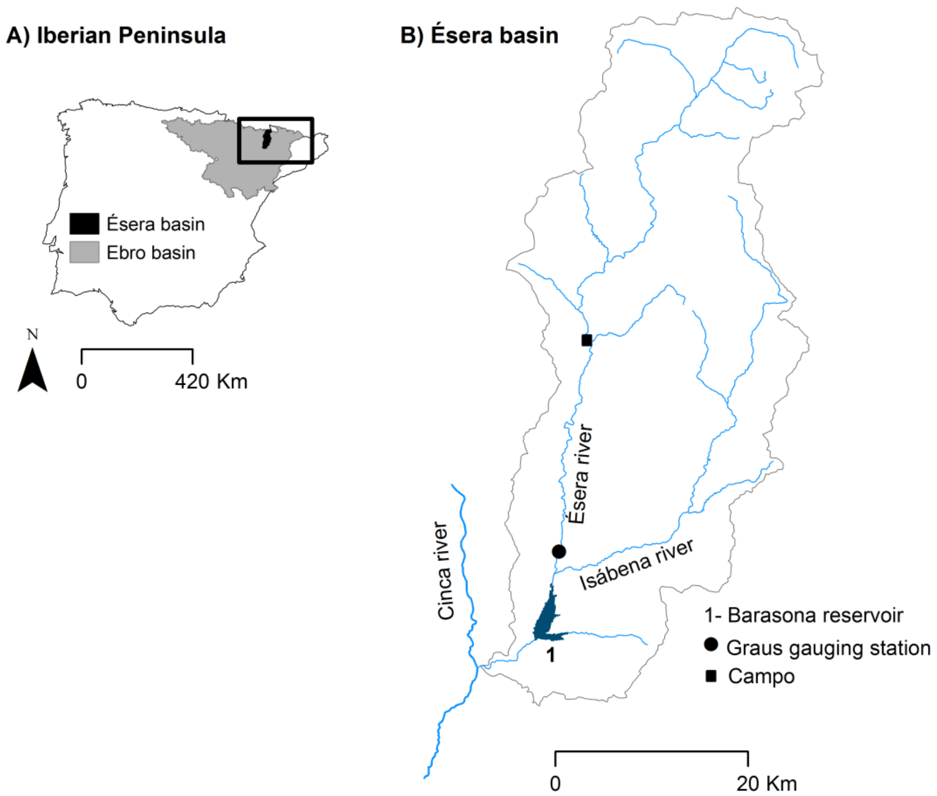

Figure 6. *(A) Location of the Ésera catchment in the Iberian Peninsula; (B) Details of the Ésera drainage network and reference cites cited in the text.*

The basin has an altitude between 2,500 masl in the headwaters to 340 masl at the outlet of the basin (Fig. 7). Around 84% of the basin area is occupied by forest, mainly coniferous forest (20%), shrub or herbaceous vegetation (33%). Floodplains are mainly occupied by agriculture, comprising the 15 % of its area (according to Corine Land

Cover, 2006; table 2.1). Forests remain well preserved on the north-facing slopes and every-where between 1,600-1,800 m (López-Moreno et al., 2006). They are characterised by the presence of *Pinus uncinata*, frequently forming mixed forests with *Abies alba* and *Betules* sp, with understory formed mainly by *Rhododendron ferrugineum*, *Vaccinium myrtillus* and *Calluna vulgaris*. There are some pastures distributed along the basin, where predominant species are *Festucion supinae*, *Festuca nigrescens*, *Festuca ovina*, *Festuca eskia* and *Cares sempervirens*. As in most Mediterranean regions, areas below 1,600 masl, in the valley bottoms, perched flats and steep and south-facing hillslopes, have been used for agriculture (Lasanta, 1989). After the mid-20th century, most cultivated fields were abandoned (i.e. except in the valley bottoms), which have been affected by a natural process of plant recolonization, particularly with *Buxus sempervirens*, *Genista scorpius*, *Rosa gr. Canina*, *Juniperus communis* and *Echinospartum horridum* (Vicente-Serrano et al., 2004), or have been reforested with *Pinus laricio* and *Pinus sylvestris* for land reclamation and to reduce reservoir siltation (Ortigosa et al., 1990; López-Moreno et al., 2006).

The lithology of the basin contains several geologic units organized in several elements trending WNW-ESE (Valero-Garces et al., 1999, Alatorre et al., 2010) : i) the axial zone of the Pyrenees (peaks above 3,000 masl), composed of Paleozoic rocks (quartzite, limestone, shales).; ii) the Internal Ranges, which is a huge overthrusting fold of Cretaceous and Paleogene sediments composed mainly of limestone and sandstones; iii) the Internal Depressions (Campo), which is formed on more erodible materials (mainly Eocene marls) giving a relatively smooth relief; iv) the pre-Pyrenean molasses, which are composed of continental Oligocene sediments (conglomerates, sandstones); and v) the External Ranges that bound the basin to the south, composed mainly of limestone. It is well known that the principal sediment sources of the catchment correspond to the badland strip on the Eocene marls located in the middle part of the basin which, for example, in the neighbouring Isábena catchment (i.e. both Ésera and Isábena share the same badland strip) represents less than 1% of its total area but plays a fundamental role in fine sediment transport (e.g. López-Tarazón et al., 2009, 2010, 2011; Piqué et al., 2014; Vericat et al., 2014).

Climate and hydrology

The Ésera belongs to the Continental Mediterranean domain, with cold and dry winters and hot and stormy summers, with frequently torrential rainfall events. The basin shows a clear altitudinal rainfall gradient (Fig. 7), with annual precipitation ranging from 420 mm at the lower areas to 2,500 mm at the summits. The average value for the whole catchment at around 1,069 mm, with maximum monthly values of 102 and 117 mm in October and May respectively. Minimum values of 61 and 68 mm are observed in February and July, respectively (data from the period 1950–2009 were obtained from the SIA, Integrated Water information System, Spanish Ministry of Agriculture, Food and Environment). The mean annual temperature ranges between 7 ºC in the northern Pyrenean zone to 14 ºC in the southern Mediterranean area (data from the period 1950–2009 were obtained from the SIA; Fig. 7).

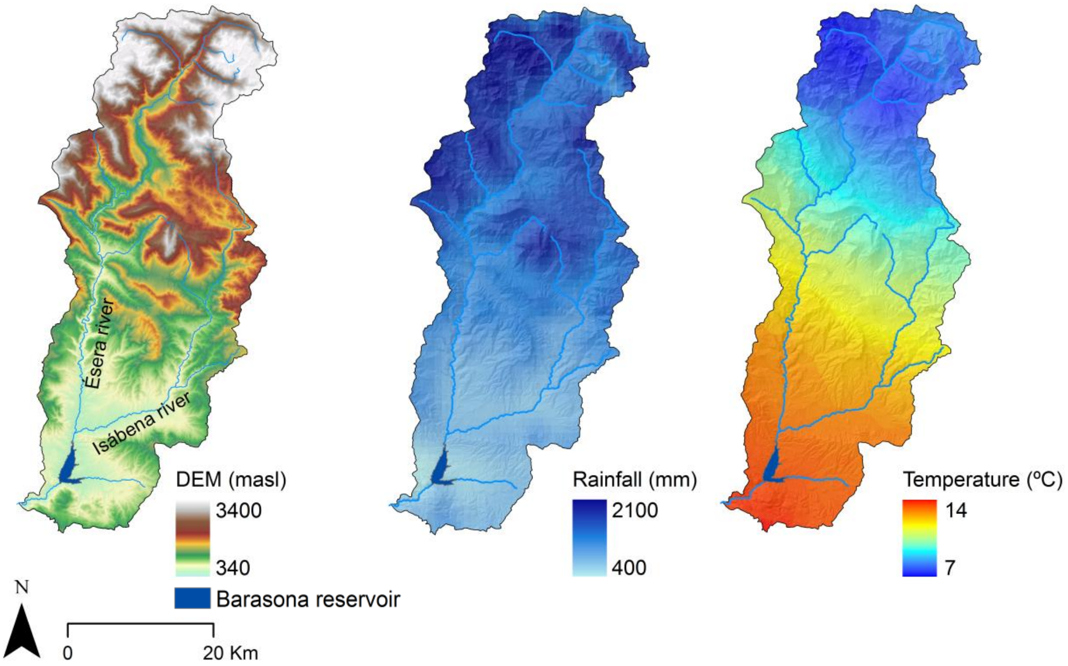

Figure 7. *(A) Digital Elevation Model (DEM) at 20 m grid resolution; (B) Mean annual rainfall (1945-2011); (C) Mean annual temperature (1945-2011).*

The hydrology of the basin is characterized by a nivo-pluvial regime. Floods normally take place in spring, mainly as a result of large frontal precipitation events and snowmelt and, especially, in late summer and autumn, as a consequence of intense localized thunderstorms (Fig. 8). Discharge is measured at the official gauging station at the village of Graus (i.e. EA013, managed by the Ebro Water Authorities; Fig. 6). The mean annual discharge is 19 m^3 s^{-1} (σ = 6 m^3 s^{-1}) for the period of record (1949-2013). Maximum peak flow measured (i.e. August 1963) was 995 m^3 s^{-1} (a discharge with a recurrence interval larger than 100 years, calculated from the series of annual maximum instantaneous flows for the period 1949-2007 and by using the Gumbel method). It is worth noting that the presence of daily flow fluctuations (i.e. hydropeaking) generated on a small weir located around 30 km upstream the village of Campo. These flow peaks are produced for hydropower generation and have variable duration depending on the local demand. Discharges attributed to these can range between 1 and 24 m^3 s^{-1}.

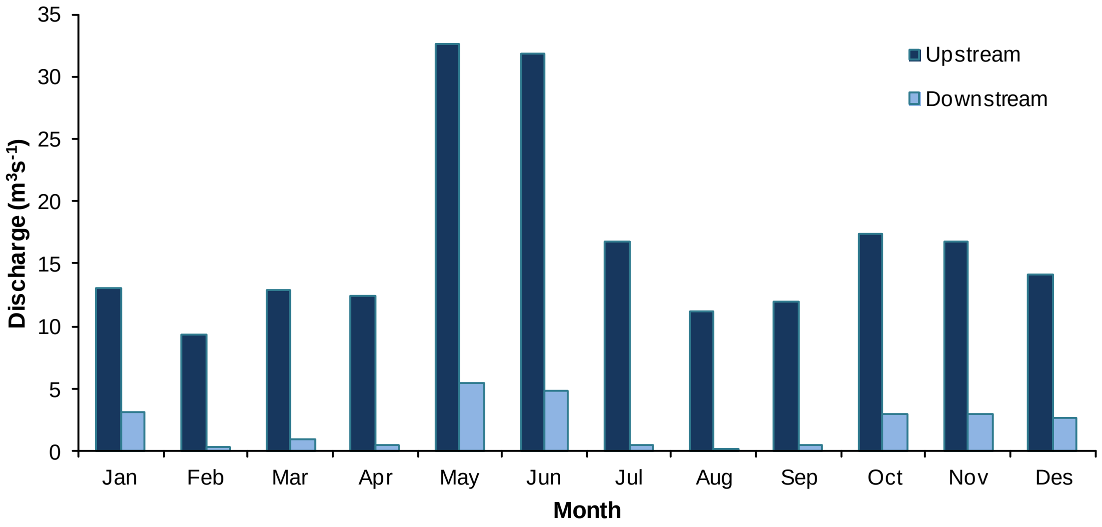

Figure 8*. Mean monthly discharge in the River Ésera upstream and downstream the Barasona Reservoir during the period 1991-2013.*

Mean annual water yield is around 600 hm^3 (σ = 190 hm^3), which represents around 4% of the total runoff in the whole Ebro basin. The main tributary of the Ésera is the River Isábena, with their confluence located few hundred meters upstream from the Barasona reservoir (Fig. 6). Mean annual discharge of the Isábena basin is 4.1 m^3 s^{-1}, while the maximum instantaneous discharge is 370 m^3 s^{-1} (registered in August 1963). Its mean water yield is around 170 hm^3, which represents 25% of the water flowing into the Barasona Reservoir.

The Barasona reservoir (Fig. 6) impounds 96% of the total area of the Ésera. It was built in 1932 for irrigation purposes and power generation. The initial water capacity was 71 hm^3, but it was enlarged in 1972 providing a final storage capacity of 92 hm^3, regulating up to 15% of the mean annual runoff (Batalla et al., 2004). The dam is mainly operated to supply water to the Aragón and Catalunya Canal, which irrigates more than 100,000 ha of agricultural areas in the lowlands. The irrigation season extends from March to October, with a maximum demand in May, July and August. Since its construction, the reservoir experiences acute siltation problems at a rate between 0.3 and 0.5 hm^3 of sediment deposited annually (Francke, 2009). A bathymetric survey of the reservoir in 1993 indicated that its original storage capacity had been reduced by 16 hm^3 (Mamede et al., 2008). Engineering works were carried out between 1995 and 1997 to release sediment through the dam bottom outlet gate. These operations finally resulted in more than 9 hm^3 of sediment sluiced down through the dam (Palau, 1998; Avendaño et al., 2000). However, it has been estimated that the current reservoir capacity equals to that prior the sluicing operations, at around 76 hm^3 (Mamede, 2008).

Barasona Reservoir clearly modifies the flow regime of the Ésera (Fig. 8). Flow is dramatically reduced, from a mean value upstream of 17.6 m^3 s^{-1} to 0.3 m^3 s^{-1} downstream. Downstream, flow only exceeded 1 m^3s^{-1} 33 days per year during the period 1991-2013 (data provided by the Ebro Water Authorities). This is mainly due that the water flowing through the river channel downstream the dam is just provided by ecological flows (filtrations). Maximum discharge recorded (a water release from the dam in 1997) was 505 m^3 s^{-1} (corresponding to a recurrence interval of 100 years calculated by the Gumbel method using the series of annual maximum daily discharge for the period 1992-2012). Mean water yield downstream from the dam is 69 hm^3, representing 9% of the Ésera water yield (including the River Isábena).

1. 2. 2. The River Siurana

Location and general characteristics

The River Siurana drains an area of 610 km^2. This river is considered the main tributary of the Lower Ebro River downstream the Mequinenza-Ribarroja-Flix Dam Complex (Fig. 9). The river flows along 58 km from the Prades mountains (1000 masl) to the lower River Ebro near the village of Garcia. Its main tributaries are the Cortiella and Asmat on the true left hand and Montsant on the true right hand. There are three reservoirs on the basin: the Siurana (located in the River Siurana; 12 hm^3), the Margalef (located in the River Montsant; 2.84 hm^3) and the Guiamets (located in the River Cortiella; 10 hm^3).

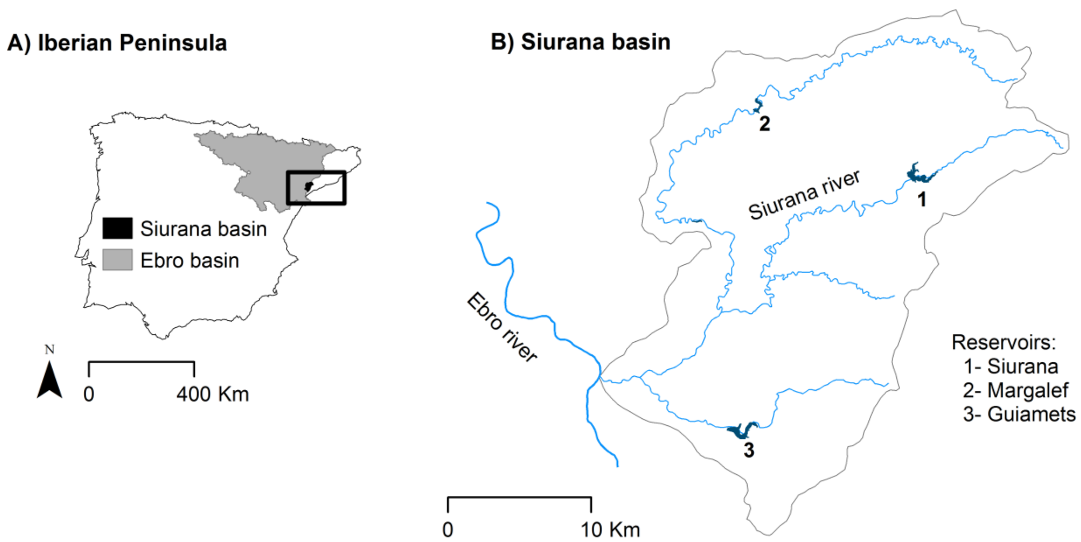

Figure 9. *(A) Location of the Siurana catchment in the Iberian Peninsula; (B) Siurana drainage network*

Altitude in the catchment ranges from more than 1,200 masl in the headwaters to 30 masl in the basin outlet. Around 49% of the basin is occupied by forest and natural vegetation, mainly coniferous forests (17%), and sclerophyllous vegetation (12%) and transitional woodland scrub (13%) (Corine Land Cover, 2006). The potential vegetation is composed by different Mediterranean oaks (e.g. *Quercus ilex*, *Quercus rotundifolia*, *Quercus faginea*). However, currently it has been replaced by *Pinus halepensis* in the lower part of the basin, and by *Pinus sylvestris* and *Pinus nigra* in the upper areas. The predominant species of shrubs are: *Quercus coccifera*, *Pistacio lentiscus*, *Daphne gnidium*, *Rubia peregrina*, *Smilax aspera*, *Euphorbia characias, Brachypodium retusum*, *Rosmarinus officinalis* and *Thymus vulgaris*. The agriculture occupies the 49% of the basin, the most abundant categories are complex cultivation patterns (39%), fruit trees (2%) and vineyards (1.2%). After the mid-20th century, most cultivated fields were abandoned (i.e. except in the valley bottoms), with a resulting increase in forest cover.

The basin is located in the Iberian domain of the Maestrazgo-Catalánides. It is mainly composed by Paleozoic slate, quartzite and sandstone, whereas the River Montsant is dominated by Paleozoic conglomerates and marls. Marls, chalks, limestone and dolomites are the predominant lithology in the Siurana headwaters. Finally, the lower most part of the basin is dominated by marls and conglomerates.

Climate and hydrology

The climate is purely Mediterranean, characterized by highly irregular rainfall patterns with marked differences between wet and dry seasons. Mean annual rainfall for the whole basin is 500 mm, with maximum monthly values of 68 and 62 mm in October and May respectively (data from the period 1950–2009 were obtained from the SIA). Minimum values of around 23 and 12 mm are registered in February and July respectively (Fig. 10). Rainfall regime is mainly characterized by its torrentiality driven by heavy thunderstorms during spring and autumn. Short and intense storms often occur locally, and it has a direct effect on flooding. In October 1994, an extraordinary rainfall of 400 mm caused loss of life and serious social and environmental impacts on the basin. Mean annual temperature ranges between 13 and 16 ºC (Fig. 10). Maximum values are recorded in July and August (40 ºC) while minimum values are recorded in winter, especially in the valleys dominated by thermal inversion (-10 ºC to -15 ºC).

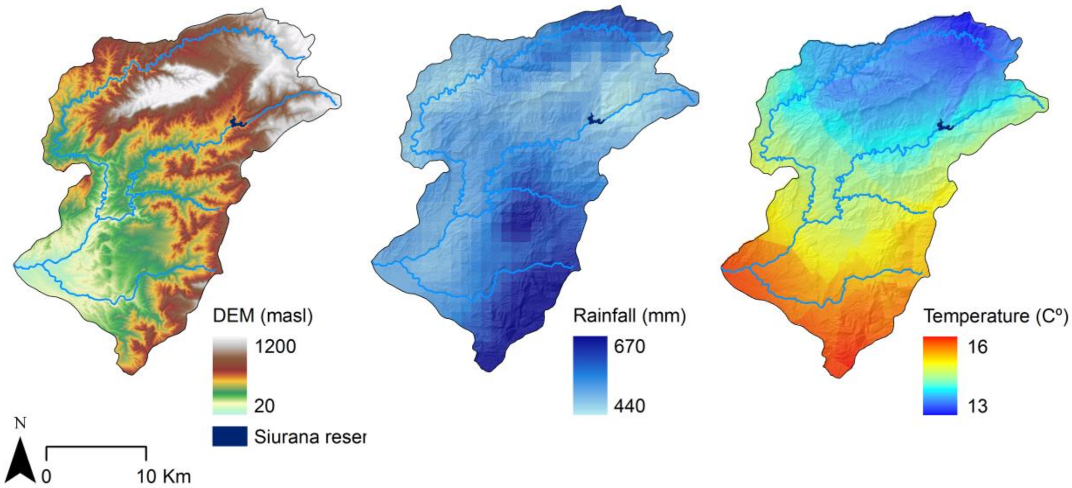

Figure 10. *(A) Digital Elevation Model (DEM) at 20 m grid resolution; (B) Mean annual rainfall (1945-2011); (C) Mean annual temperature (1945-2011).*

Mean annual water yield is 48 hm^3 y^{-1}. The basin is regulated by three reservoirs (Fig. 9). The Siurana Reservoir (i.e. drainage area of 60.4 km^2) collects water from the upper reach of the River Siurana, as well as its tributaries, the Argentera and the Estopinyà ravines. It was built in 1972 to supply water to the Riudecanyes Reservoir (inter-basin water transfer). The dam has 63 m height with a maximum storage capacity of 12 hm^3, impounding the 270% of the mean annual runoff (i.e. 4.4 hm^3). The Margalef Reservoir (i.e. drainage area of 91 km^2) is located in the upper part of the River Monstant. It was built in 1992 for irrigation and water supply, with a maximum storage capacity of 2.84 hm^3 and 33.2 m dam height. Finally, Guiamets Reservoir (drainage area of 72 km^2) was built in 1983 for irrigation supply, which collects water from the River Asmat. It has a maximum storage capacity of 10 hm^3 and 47 m dam height. Both River Montsant and River Asmat are intermittent and dries out during summer, whereas the River Siurana has reduced but uninterrupted summer flows. Three reservoirs cause a complete inversion of the flow seasonal pattern (Fig. 11), due to release water for irrigation in the summer that provokes a permanent and high discharge downstream.

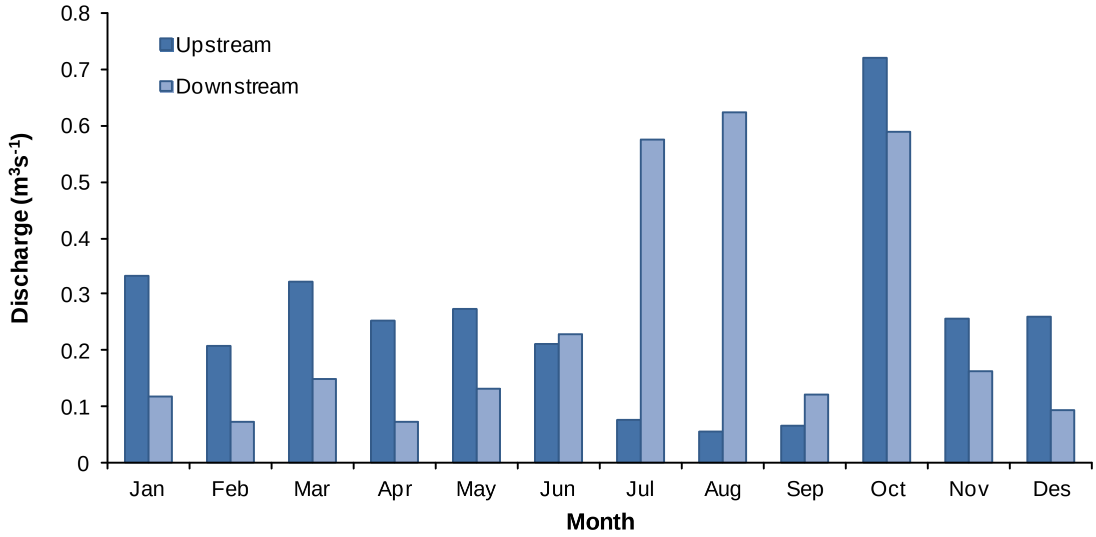

Figure 11. *Mean monthly discharge in the River Siurana upstream and downstream of the Siurana Reservoir during the period 1971-2011.*

There are no flow data available (i.e. inputs and outputs) for the Margalef and Guiamets Reservoirs, so only data from Siurana Reservoir can be analyzed. The River Siurana is representative of a rainfall-based flow regime with a marked seasonality (Fig. 11). Mean annual flow upstream the Siurana dam is around 0.25 m^3 s^{-1}, while the maximum is in October (0.7 m^3 s^{-1}) and the minimum in August (0.053 m^3 s^{-1}; inflow and outflow of the Siurana Reservoir for the period 1971-2011 obtained from the Catalan Water Agency). Floods usually taken place during spring and autumn (i.e. localized thunderstorms) with a maximum discharge of 135 m^3 s^{-1} recorded in October 1994 (i.e. discharge with a recurrence interval of more than 100 years, calculated using the series of the annual maximum daily discharge for the period 1949-2007 and the Gumbel method). Mean annual discharge recorded downstream from the dam is 0.24 m^3 s^{-1}, a value very similar to that registered in upstream. However, the maximum discharge recorded downstream was substantially lower to that of upstream (i.e. 83 m^3 s^{-1} registered on October 1994). The seasonality of the river flow is also altered, especially in summer. During summer, the upstream section has its lowest flows (ie. the inputs to the reservoir are low or non-existent), while the downstream reach experiences its highest flows, due to the reservoir releases (Fig. 11).

2. METHODS

2. 1. Overview

Data acquisition design was structured in two components: i) sampling and ii) monitoring. An extensive hydrological and geomorphological characterization was undertaken in 74 sites (including regulated and not regulated sites) distributed along the four large Mediterranean catchments described above in section 2.1 (Ebro, Llobregat, Júcar and Guadalquivir). Additionally, a detailed and continuous monitoring of ecological and geomorphological variables was undertaken in two rivers with contrasting Mediterranean flow regimes: the Ésera and the Siurana, both located in the Ebro basin (the rivers introduced in section 2.2). Four river reaches were selected for monitoring, located upstream and downstream of the Barasona Reservoir (River Ésera) and the Siurana Reservoir (River Siurana). Fig. 12 shows the main data acquired under each of the components and their relation with the different objectives of the thesis. It is worth mentioning that each paper presents the specific description of the methods. Here all methods are generally introduced with the objective to link them with the different specific objectives of the thesis.

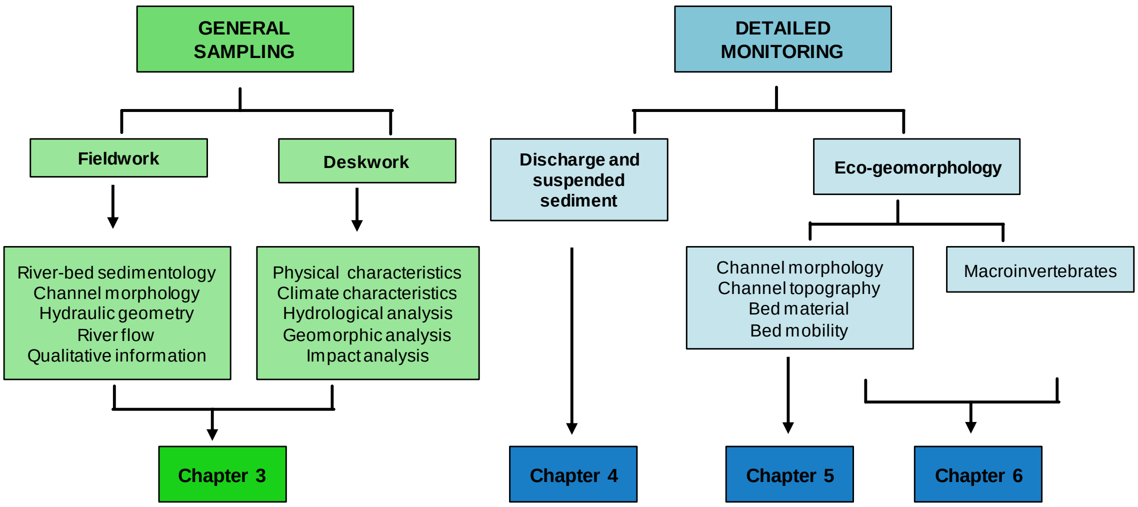

Figure 12. *Data acquisition design and intercation with the different chapters of the thesis.*

2. 2. Sampling

Data acquired under this component have the main objective to examine the effects of the dams on the channel geomorphology in selected river reaches in the Iberian Peninsula. Based on this objective, sampling included: i) physical and climate characterization of the study sites; ii) hydrological and geomorphic effects of dams; and iii) characterization of channel morphology, sedimentary structure and river sedimentology (e.g. incision and armouring). A specific description of these data is extensively explained in Chapter 3 (Geomorphic status of regulated rivers in the Iberian Peninsula) so just a brief presentation is given here (see Chapter 3 for a detailed description).

A 74 general sampling locations (Fig. 13) were selected based on three main criteria (i.e. SCARCE project study sites): i) Degree of Mediterraneity: Total rainfall, intensity and temporal variability; ii) Degree and type of impact: Flow regulation has been considered the main impact for the study; and iii) Historical data availability: Historical data is of great interest to analyse long term morphosedimentary changes and patterns and their drivers.

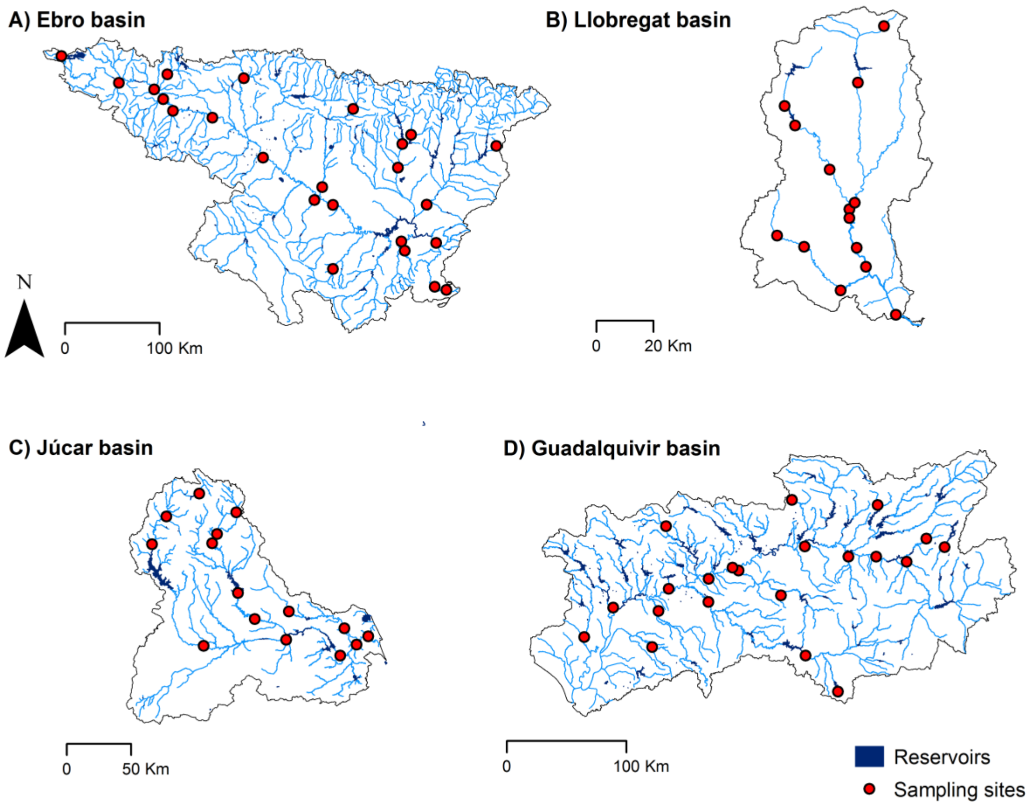

Figure 13. *Location of the study sites and reservoirs in the study catchments (Ebro, Llobregat, Júcar and Guadalquivir).*

2. 2. 1. Fieldwork

An extensive field campaign was undertaken during 2010-2011 at the 74 study sites presented in Fig. 13. The sampling strategy was directed to measure and describe the variables and indicators considered the most relevant for the rivers' physical characterization: i) river bed sedimentology, ii) channel morphology, iii) hydraulic geometry and river flow, together with iv) some qualitative information related to vegetation and quality indexes.

Bed material characterization

Surface and subsurface materials were characterized independently. Surface material has been characterised by means of the pebble-count method (Wolman, 1954). This method is based on measuring the *b*-axis of at least 100 particles in each morphological unit. Samples were measured using a gravel template with squared holes of ½ phi unit classes following the Wentworth scale. Nevertheless, the pebble-count technique underestimates the proportion of material less than 8 mm, so material smaller than this size was not considered. At all reaches containing exposed bars, the surface material was additionally measured with an indirect method. This consisted of taking plan-view photography of a scaled patch. These images were subsequently analysed using the Digital Gravelometer®. This software is used to characterise the surface grain-size distribution and to obtain the statistical parameters of the sediments as well as its surface structure.

Subsurface materials were sampled using the volumetric method (Church et al., 1987) in reaches containing exposed bars. A representative patch of the bar was spray-painted to differentiate the surface from the subsurface material (following Lane and Carlson, 1953). The sampled area was 1 m^2 and the volume of the subsurface sample depends on the weight of the largest particle in the subsurface. On average, largest particle sizes represented less than 1% of the total sampled weight (Church et al., 1987).The coarser material was sieved in the field while the finer material (<4 mm) was taken to the laboratory where it was dried and sieved. Both materials were later classified in different size classes according to the Wentworth scale.

Additionally to surface and subsurface sediments, surface patches of fine sediments were also characterised if present. Volumetric samples of these were taken and processed in the laboratory to obtain GSDs.

Channel morphology

Channel morphology was analysed by means of several topographic measurements at the different morphological units previously identified: riffle, pool, plain-bed, transition zone, and bars. The identification of the morphological units was done based on the morphological classification proposed by Montgomery and Buffington (1997). Total sampling length was composed by at least one morphological sequence (e.g., riffle/pool/plain bed). Simultaneously, notes and sketches were made in order to obtain qualitative data related to vegetation, local perturbations and infrastructures (for which see details in the paragraph below).

Channel geometry, flow velocity and discharge

A minimum of five cross sections were surveyed in each study site when the channel was wadeable. Water surface elevation and the local channel slope were also surveyed. Surveys were obtained by means of a Geodimeter® 422 Total Station and a Leica® TCRP1201 Robotic Total Station. Sections were selected based on the morphological units. Additional observations (e.g., water edges, banks, substrate type) were made in order to get a detailed description of each section. Flow velocity was characterised by means of velocity profiles measured in each cross section using an electromagnetic velocity meter (Valeport 801). The number of profiles in each section varied according to the width, shape and complexity of the channel. Velocity measurements were done at 0.4 times water depth (from the bed), which theoretically corresponds with the location of the mean velocity. Additional verticals were taken when velocity measurements were highly variable.

Human impacts and riparian corridor

Channel impacts (e.g. dams, dykes, bridges and evidence of gravel mining) and other human perturbations (e.g. water abstraction) were assessed during field surveys. In addition, channel and riparian vegetation was analysed in terms of composition and structure, and both longitudinal and lateral connectivity was assessed (Elosegi and Díez, 2009). A simple method was applied consisting in the visual estimation of the coverage of submerged and emergent vegetation and the identification of the dominant species. In addition, the longitudinal continuity and width of the riparian vegetation along the reach, its composition (dominant both native and exotic species), structure, and connection with the channel were assessed (Elosegi and Díez, 2009).

2. 2. 2. Data analyses

Physical and climate characterization

Physical characteristics measured in each study site include drainage area, length of the stream network, stream order and mean basin slope. These analyses were based on Digital Elevation Models (DEM) of 20 and 30 meters resolution. Data were obtained from the corresponding Water Agency of each catchment. In addition, the Gravelius index (i.e. defined as the relation between the basin area and the corresponding catchment perimeter) was calculated to assess the basin shape. The geological characteristics of the catchments were described with the average Rock Resistance

Class value following Clayton and Shamoon (1998). Data were based on the features of the 1:1,000,000 Geological Map of the Iberian Peninsula (Spanish Geological and Mining Institute - IGME). The Rock Resistance Index classifies lithologies in six classes according to their resistance to erosion (i.e. 1 very weak to 6 very resistant). Climate data were obtained from monthly precipitation and evapotranspiration rasters of 1 km pixel resolution for the period 1950–2009. Data were available at the SIA (Integrated Water information System, Spanish Ministry of Agriculture, Food and Environment). Several climatic variables were calculated based on these data: mean annual precipitation, Aridity Index (i.e. ratio between mean annual precipitation and mean annual evapotranspiration) and the coefficient of variation between monthly precipitation means. Physical and climatic characteristics of each drainage area were analyzed using ESRI® ArcMap™ 9.3.

Hydrological and geomorphological characterization

Hydrological data were obtained from daily streamflow series compiled from various Water Agencies in Spain (i.e. Ebro, Júcar and Guadalquivir Water Authorities and the Catalan Water Agency). Daily flows were analyzed using the Indicators of Hydrologic Alteration (IHA) software (Richter et al., 1996; Mathews and Richter, 2007) that produces more than 30 variables. Additional parameters were calculated: flood recurrence intervals of 2, 10 and 25 years, and basin torrentiality (i.e. taken as a proxy of the Mediterranean character of the basin). Torrentiality is represented by the ratio between the mean of the maximum discharges in the series and the average discharge of the whole data set. The Impoundment Ratio (IR, as per Batalla et al., 2004) was assessed in order to estimate the degree of the hydrological impact affecting each site. IR is defined as the ratio between the reservoir storage volume and the mean annual runoff. Reservoir capacity and mean annual runoff were obtained from respective water agencies. Mean annual runoff, where official flow records were not available, was obtained from the CEDEX-SIMPA Rainfall–Runoff Integrated Modelling System (Centre of Hydrographic Studies of CEDEX). Furthermore, other relevant parameters, such as the distance from the dam to the study site and the number of tributaries between the dam and the site, were calculated.

The geomorphic status of the study areas was assessed from aerial photographs from the 1970s and 2011. A new index to assess the geomorphological status of impacted rivers has been developed for this thesis (details in Chapter 3). As a general information, images from the late 1970s, freely available at the National Geographical Institute (IGN) web site (www.ign.es), were taken as the reference image (i.e. most dams in Spain were built between 1960 and 1970s and we considered the geomorphology of the river reaches downstream from the dams not yet severely affected). The current images (i.e. 2011) were also obtained through the IGN web site by using the 'Iberpix Viewer'. Morphological units (active bars) and physical variables (e.g. active channel width) were measured in each image. The comparison between both images was used to develop a new geomorphic status index as detailed in Chapter 3.

2. 3. Monitoring

Field monitoring was conducted in the Ésera and the Siurana. These catchments are located in the Ebro basin and have contrasting hydroclimatic characteristics. Two sections were monitored in each catchment following a control-impact design (Fig. 14): upstream (ESE_{US}) and downstream (ESE_{DS}) of the Barasona Reservoir in the Ésera; and upstream (SIU_{US}) and downstream (SIU_{DS}) of the Siurana Reservoir in the Siurana.

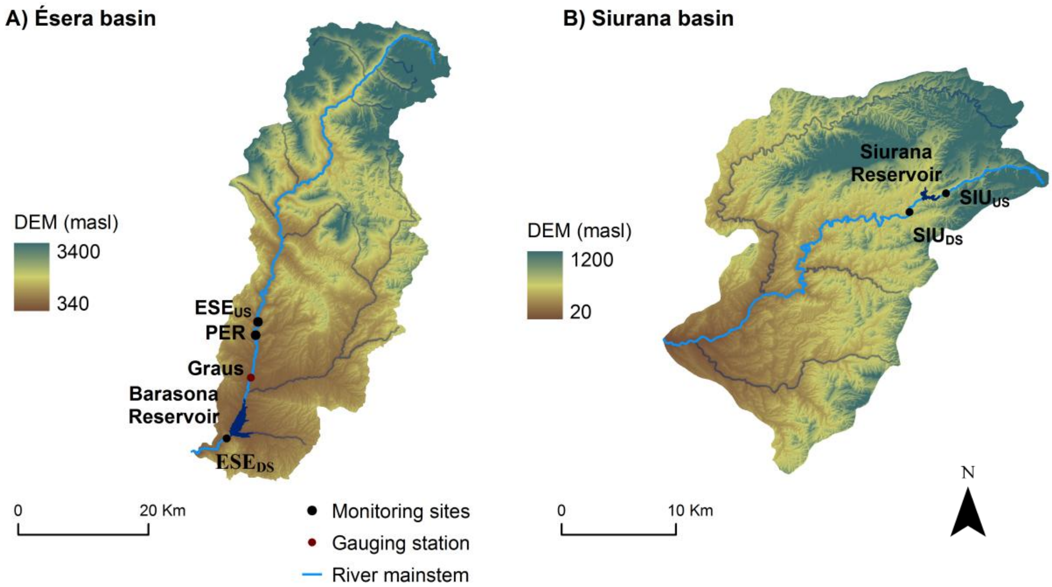

Figure 14. *General map of the Ésera (A) and the Siurana (B) catchments and the locations of all the monitoring stations.*

2. 3. 1. Flow and sediment transport

Discharge and suspended sediment concentration (*SSC*) were continuously monitored from October 2011 to October 2013 at all study sites. Such data form the basis of Chapter 4 (Sediment transport in two Mediterranean regulated rivers). Water stage was measured by 2 different ways depending on the available infrastructure: i) at ESE_{US}, flow data was fully provided by the Ebro Water Authorities (CHE), which measures water depths continuously at the Graus gauging station (EA013, located 3 km upstream the reservoir located upstream from the confluence with the River Isábena, Fig. 14). Water stage was recorded at 15-min intervals and then transformed into discharge (*Q*) by using the corresponding water stage/discharge (i.e. *h/Q*) rating curve.

A the remainder of the monitoring stations (ESE_{DS}, SIU_{US} and SIU_{DS}) ii) water stage was measured by means of capacitive water stage sensors equipped with an internal logger (Trutrack® WT-HR, Fig. 15). Flow was recorded at a 15-min interval and was later converted into *Q* by applying at-a-site *h/Q* rating curves obtained combining direct measurements, modelling and data from nearby hydrometric stations. Repeated field discharge gauging and topographical surveys were made at each site. Direct flow-measurements were made by means of an electromagnetic current meter (Valeport® 801) or an acoustic Doppler current profiler (aDcp (Sontek River surveyor M9®)).

Figure 15. *(A) Official gauging station of the River Ésera in Graus (EA013); (B) SIU_{US} suspended sediment transport installation used as an example of the other stations; note that the water stage sampler (i.e., Trutrack®) is installed inside the dark PVC tube; the turbidimeter inside the metallic tube); (C) Automatic water sampler ISCO 3700; (D) Examples of filters after processing.*

Suspended Sediment Concentrations (*SSC*) were derived from turbidity records obtained by low-range turbidimeters (McVann® ANALITE NEP-9350 (measuring range 0-3000 NTU ≈ 3 g l^{-1})) at those places in which maximum *SSCs* were not supposed to exceed moderate values (ESE_{DS}, SIU_{US} and SIU_{DS}), whereas a high range back-scattering Endress+Hausser® Turbimax WCUS41 turbidimeter (up to 300 g l^{-1}) was installed in ESE_{US} where high *SSCs* were expected (as in the neighbour River Isábena as reported by López-Tarazón et al., 2009). Field visits (i.e. every two weeks) were performed for maintenance (e.g. equipment malfunctioning, replacing batteries, lens cleaning, and data downloading). Water turbidity is an “expression of the optical property of the water that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample"; it can be defined as the "reduction of transparency of a liquid caused by the presence of particulate matter (i.e., clays, soluble organic composites, plankton, microorganisms) being, this way, the opposite of clarity" (Lawler, 2005; López-Tarazón, 2011). Turbidity was measured in Nephelometric Turbidity Units (NTU); these units do not have direct transformation to *SSC*, but they can be converted into suspended sediment concentration by means of field calibrations (as explained in the following section). Campbell data-loggers (CR-200 and CR-500) were linked to the turbidity probes to record the average turbidity values taken every 1 minute at 15 min intervals.

Water samples were collected intensively during flood events and routinely during low flows. Samples were collected (i) manually, by means of a depth integrated suspended sediment sampler (DH-59) or by means a bucket sampler, and (ii) automatically, by means of an automatic water sampler (ISCO® 3700; Fig. 15). The automatic sampler was able to take up to 24 bottles of 1 litre at a predetermined frequency when flow reached the liquid level actuator. Samples were labelled and brought to the lab to be post-processed. They were vacuum filtered in cellulose and glass microfiber filters (Filter-Lab, 0.0012 mm pore size). Finally, all samples were dried and weighted to determine the *SSC* (Fig. 15). The organic matter content was assessed and subtracted from the final dried filter weight. To differentiate between organic and inorganic fractions, filters were burnt at 450 ºC for 5 h in an oven (Tena et al., 2011). Once the organic matter was eliminated from each filter, relations between the percentage of organic matter, flow and *SSC* were examined. These relationships were applied in order to group *SSC* samples and to remove the organic matter. In case these relationships were not evident, the average of the organic matter of the analysed samples was used to correct the *SSCs*. Correlation between the turbidity registers (i.e. NTU) and the *SSCs* of all the samples were established for each turbidimeter (Fig. 16). In the case of the low-range turbidimeters, calibrations followed a linear regression (SSC = a × NTU + b, where *a* varies from 0.006 to 0.8275 and *b* from -0.0091 to 0.0015) with coefficients of determination (r^2) ranging from 0.81 to 0.98. In the case of the high-range turbidimeter the best fit to the data (r^2 = 0.91) was obtained by a polynomial regression (SSC = 0.1736 × NTU 2 + 0.781 × NTU).

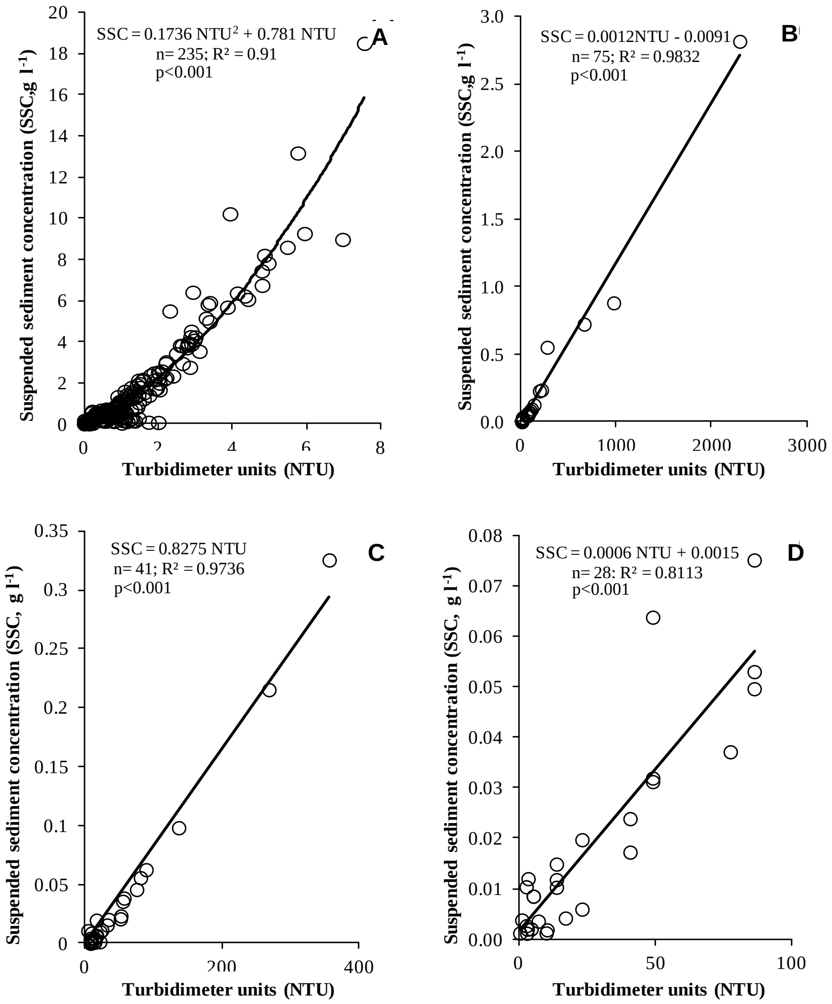

***Figure 16**. Turbidimeter calibrations obtained between pairs of values of turbidity measurements (NTU) and measured suspended sediment concentration (SSC) from water samples at (A) ESE_{US}, (B) ESE_{DS}, (C) SIU_{US}, and (D) SIU_{DS}. Resulting equations, together with the number of samples used (i.e. N) and the statistical significance are also shown.*

2. 3. 2. Eco-geomorphology

Ecological and geomorphological properties were analysed upstream and downstream from dams in the Ésera and Siurana rivers during a 2-yr period (2011-2013). The geomorphological properties included channel morphology and topography, river-bed texture and bed mobility. These data, together with flow and channel hydraulics were the basis of Chapter 5 *(Bed disturbance below dams: observations from two Mediterranean Rivers).* Ecologically, invertebrate communities and trait composition were examined in the Siurana catchment, upstream and downstream. These variables were analysed based on the geomorphological dynamics in each reach, being the basis of Chapter 6 *(Effects of flow regulation on river bed dynamics and invertebrate communities in a Mediterranean River).*

Channel morphology and topography

Channel morphology was characterised following the methods described in section 2.1.1. In addition, close range aerial photographs were obtained at all reaches by a camera attached to a helium-balloon (Fig. 17), georectified and mosaicked following the approach described by Vericat et al. (2009). These photographs were used to map the morphological units of the reaches and then calculate the extension of the each unit, substrate and habitat. Channel topography has been characterized with the objective of obtaining a continuous and detailed topographic model of the study reaches (i.e. Digital Elevation Model, DEM) after channel disturbances. The objective here was to study geomorphic changes related to flood events. Such DEMs were also used to parameterize the hydraulic models used to accomplish specific objectives of one of the publications of the thesis (see details in Chapter 5). Topographic surveys were performed by means of a Leica® GNSS/GPS, Leica® TCRP1201 Robotic Total Station and a Terrestrial Laser Scanning Leica® ScanStation (Fig. 17), and are complemented by bathymetric surveys performed using an aDcp (Sontek River surveyor M9®) in non- wadeables areas (e.g. deep pools). A primary topographic network control was established in each monitoring section. All topographical surveys were registered to this network, maintaining the coordinate system for all survey occasions (Fig. 18). The coordinates of each ground control point were post-processed using the RINEX files of the reference stations of the *Sistema de Información Territorial de Aragón* and of the *Institut Cartogràfic de Catalunya*. The 3D quality of the control points was smaller than 1 cm. The Local Base or Reference Station for the rtk-GPS was established in one of the control points. Survey observations with 3D qualities greater than 5 cm were not registered.

Figure 17. *(A) Local Base or Reference GPS Station used to correct rtk-GPS-based observations (Leica® GNSS/GPS); (B) Leica® TCRP1201 Robotic Total Station; (C) Terrestrial Laser Scanning Leica® ScanStationC10; (D) Digital camera attached to a helium balloon to acquire close range aerial photographs.*

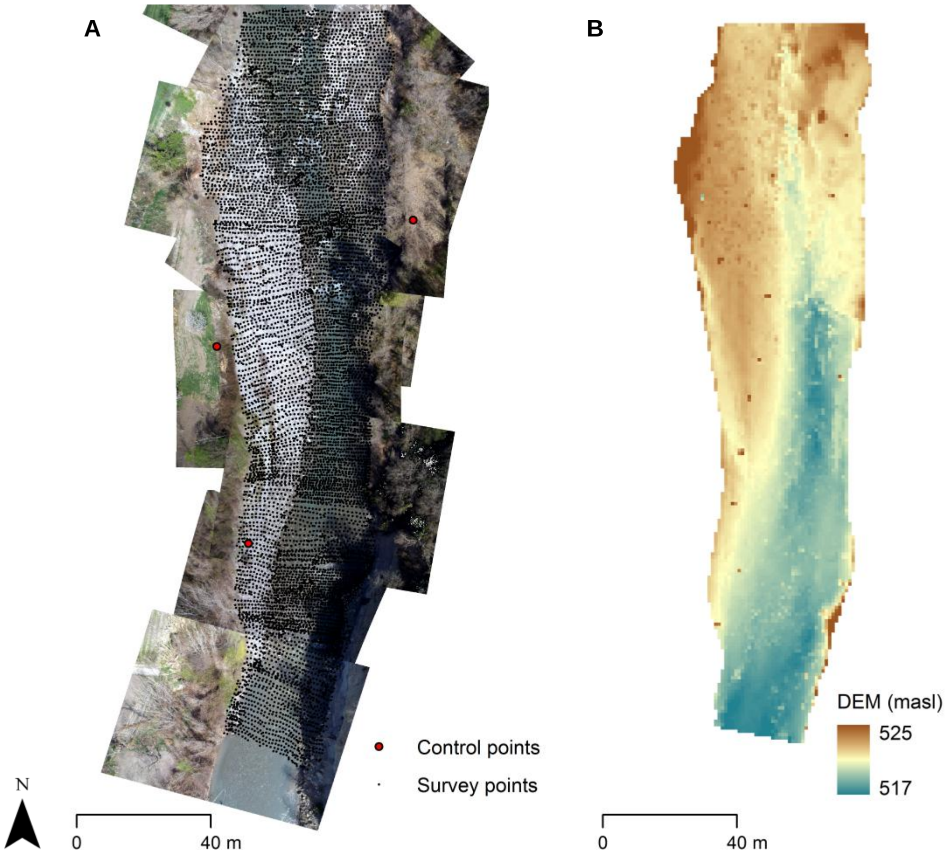

Figure 18. *(A) Aerial image of the ESE_{US} taken from a BLIMP, with the high density survey and location of the control points; (B) Digital Elevation Model (DEM) of the same reach.*

All surveys were post-processed by the Leica Geo Office® software. Data were converted to the projected coordinate system UTM-ETRS89 (zone 31). The density of the topographical observations varied between reaches, ranging from 0.5 to 3.4 points m^{-2} (Table 2). To complement the data for the terrain outside the river channel the 5x5 m DEM of the *Instituto Geográfico Nacional* was used. From the topographic surveys, a triangulation process was followed to produce TINs (by using the ESRI™ software ArcGIS™) which were resampled to a grid by linear interpolation to finally create 1 m resolution rasters or DEMs. DEMs were compared (DEM of Difference, DoD) in order to study topographic changes associated with flood events. DEM quality can be potentially affected by the interpolation and other factors like survey point quality, sampling strategy, surface composition and topographic complexity (Wheaton et al., 2010). Analyses of DEM uncertainty and their propagation to the DoD are essential to distinguish real geomorphic changes from noise. DEM quality (error) was assessed following the approach presented by Brasington et al. (2000) and Wheaton et al. (2010), which is explained extensively in Chapter 5.

Table 2

Summary of topographical surveys obtained in all study reaches (ESE_{US}, ESE_{DS}, SIU_{US}, SIU_{DS})

Site	**Topographical surveys**	**Survey area (m^2)**	**Total observations**	**Final density (points m^{-2})**	**Mean error of the DEM[1] (m)**
ESE_{US}	T0	9,070	10,575	1.16	0.13
	T1	9,181	15,559	1.70	0.11
	T2	8,618	6,869	0.80	0.11
	T3	2,986	2,976	1.00	0.09
	T4	9,181	10,388	1.13	0.15
ESE_{DS}	T0	2,147	2,814	1.31	0.27
	T1	2,147	2,600	1.21	0.22
SIU_{US}	T0	2,091	5,251	2.51	0.11
	T1	2,091	1,843	0.88	0.12
	T2	2,091	1,018	0.50	0.13
	T3	1,310	1,360	1.04	0.12
	T4	2,091	2,726	1.30	0.20
SIU_{DS}	T0	356	1,207	3.39	0.15
	T1	356	500	1.4	0.06

[1] Digital Elevation Model (DEM). Mean error is estimated as mean of the residual between the 5% of the total observations (observed topography) and the DEM calculated with the remained 95% of the survey observations (modelled).

River bed material characterization and bed mobility

The grain size distribution of bed materials was determined in each morphological unit (e.g. bar, riffle, pool) of each study reach after each potentially competent flood event. The objective was to assess changes in the texture of the channel through time in relation to flood events. Surface and subsurface materials were characterised following the methods described in section 2. 1. 1.

Bed mobility was assessed by means of tracers (e.g. Church and Hassan, 1992). Different types of tracers were employed depending on channel characteristics. Here, a *tracer* is the particle (i.e. gravels or pebbles) that is tagged with the objective of controlling its movement and trajectory associated to competent events. Tagging can be done by means of different techniques (see the review by Hassan and Ergenzinzer, 2003). Painted tracers were used at all sections, using 2 different approaches to position them: i) painted areas: square areas of a known dimension were distributed at different places of the bar with the objective to trace most of the grain-size fractions of the bed (Fig. 19 and 20); and ii) lines of painted gravels: groups of gravels of different size were positioned in a straight line, perpendicular to the flow. In the first approach the sedimentary structure is not altered, while in the second the structure is altered. The latter was an approach used mainly in the wet channel where the bed could not be painted.

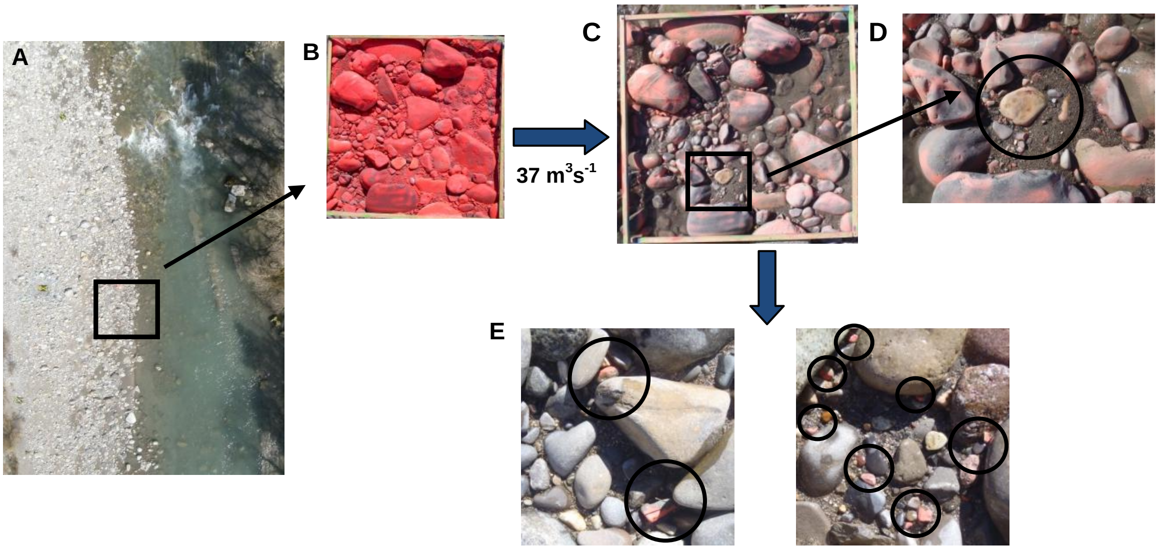

Figure 19. *Example of a painted tracer's mobility in the River Ésera upstream from Barasona reservoir (ESE_{US}) after a discharge of 37 m^3s^{-1}. (A) Aerial photograph of the study reach with the location of the red painted area; (B) red painted area before the flood event; (C) red painted area after the flood event; (D) particle coming from upstream; (E) recovered tracers downstream.*

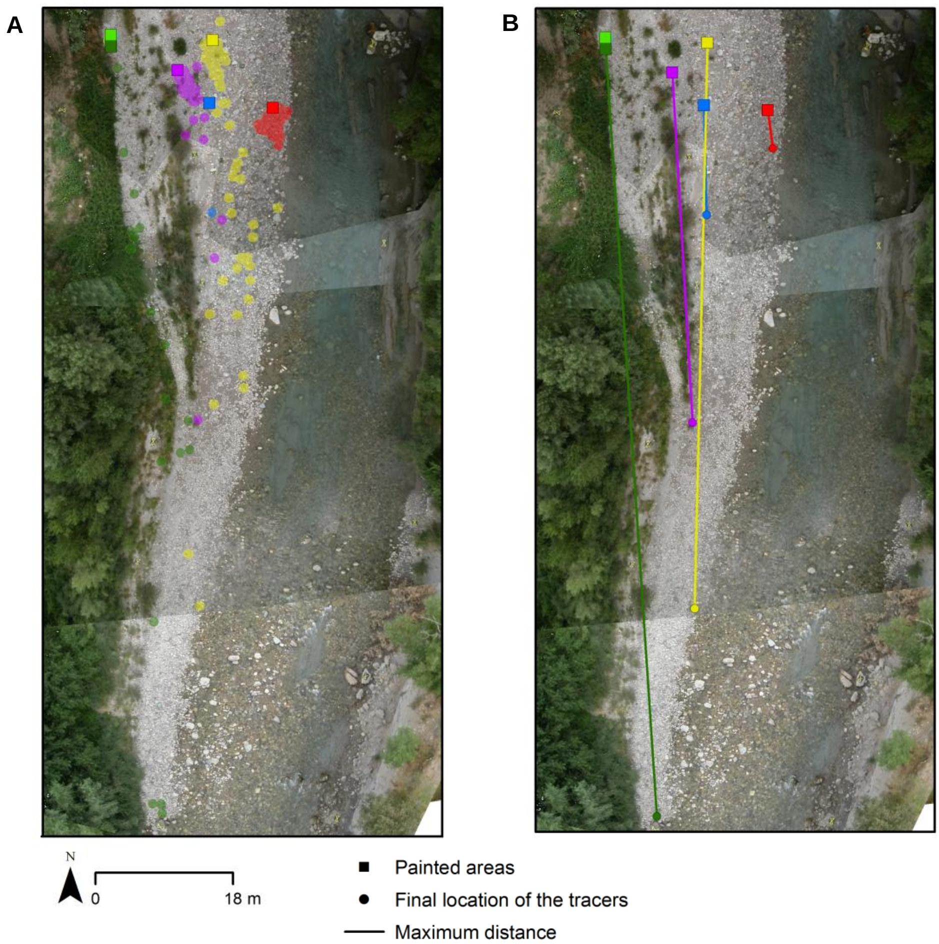

Figure 20. *Painted tracer mobility in the River Ésera upstream from Barasona reservoir (ESE_{US}) during the 2 year study period. (A) Squares show the painted areas (initial position), and dots the movement of the tracers after the floods of different magnitude; (B) Lines indicates the maximum displacement of the tracers of the different painted areas.*

Additionally, passive Radio Frequency Identification tags (i.e. RFID) were used in $SIU_{DS.}$ RFID tags were inserted to individual clasts (see more details in Nichols, 2004 and Lamarre et al., 2005). This technique was used in SIU_{DS} because the paint was rapidly abraded and particles were covered totally by biofilm. RFID tracers were located by means of a portable antenna. Once the tracer is close to the antenna the tag activates and gives its code to a reader (see system in Fig. 21). Therefore, no visual observation of the tracers was required in this case. The position of the tracers was obtained by means a rtk-GPS or Total Station if satellite reception was limited. All data were registered to the same coordinate system following the methods described above. The displacement of the tracers (i.e., particle step-length) was computed using the ESRI™ software ArcGIS™ (Fig. 20).

Figure 21. *(A) Example of the tracers with a radio system (RFID) and the antenna; (B) Example of a tracer with a RFID in the River Siurana downstream from Siurana reservoir (SIU_{DS}).*

Invertebrates

Invertebrates were sampled in one, the Siurana. Sampling was conducted at the control and impact sites (upstream and downstream from the Siurana dam, see location in Fig. 14) in just one occasion. The upstream site was used as reference assuming that this is the situation that would present the river ecosystem without the presence of the dam. Between 6 and 18 samples were collected randomly in each habitat (i.e. according to type of substrate and water velocity) in order to reduce effects of small-scale habitat variability. Invertebrates were collected using a standard Surber sampler (i.e. 300 µm of mesh size; 0.09 m^2 of area) and preserved with 70% ethanol in the field and then taken to the laboratory (Fig. 22). Invertebrates were identified to the lowest possible taxonomic level (mostly genus) following Tachet et al. (2002). Oligochaeta were identified to family level and Diptera to subfamily or tribe level. Invertebrate biomass was estimated by a length/dry mass conversion. Body length or head capsule of each individual was measured and latter related to a dry mass (mg) applying a regression function according to each specific taxon (Meyer, 1989 and

Burgherr and Meyer, 1997). The dry mass of these taxa for which the length-dry mass relations had not been previously calculated was determined following Burgherr and Meyer (1997). Several replicates of different size of each single taxon were transferred individually into weighted aluminium foils. These were dried up in an oven at 60ºC during 24h. Once these were cool (left a desiccator) were weighted to measure their dry mass.

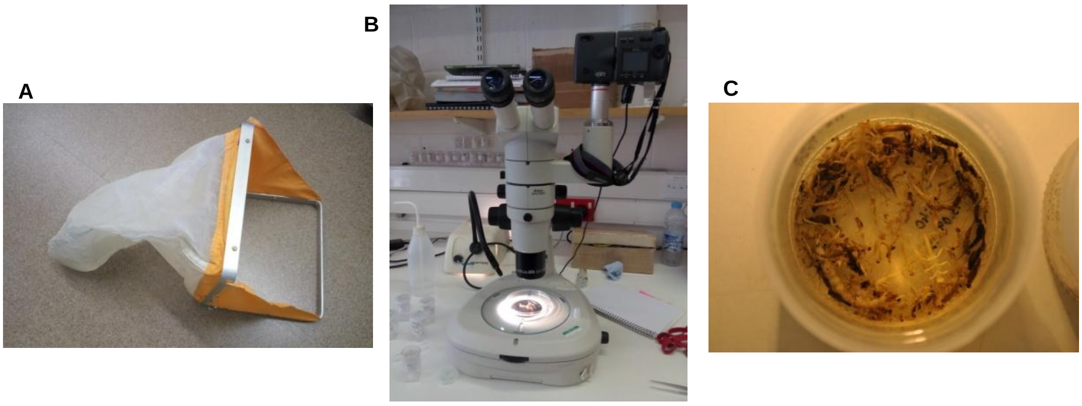

Figure 22. *(A) Example of the Surber sampler; (B,C) Identification of invertebrate taxa.*

Biological traits were used to examine the effect of regulation on the invertebrates' assemblages. Each trait was described by several categories using databases for European rivers presented in Tachet et al. (2002). The trait profile of the total taxa determined from the benthic invertebrates were described mainly at species or genus level, except for some Diptera, Oligochaeta, Gasteropode and Crustacea which were described at family or sub-family level. The main trait profile was obtained by weighting the individual trait profiles of each taxa by their logarithmic (x+1) abundance in the sample. Then, the sum of the weighted affinity scores of all the taxa of the reach (for each trait category) was calculated; finally, each sum of weighted affinity scores was expressed as a frequency per trait (Usseglio-Polatera et al., 2000; Descloux et al., 2014). Results are presented in Chapter 6.

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Relevant websites

http://www.chj.es/: Júcar Water Authorities. Data, maps and reports of the Júcar catchment

http://www.chebro.es/: Ebro Water Authorities. Data, maps and reports of the Ebro catchment.

http://www.chguadalquivir.es/: Guadalquivir Water Authorites. Data, maps and reports of the Guadalquivir catchment.

https://aca-web.gencat.cat/: Catalan Water Agency. Data, maps and reports of the Llobregat catchment.

http://parcsnaturals.gencat.cat/: Data, maps and reports of the Llobregat catchment.

Chapter 3

Geomorphic status of regulated rivers in the Iberian Peninsula

The objective of this chapter is to evaluate the effects of regulation on river-channel geomorphology in four large catchments at multiple spatial scales. The chapter contains the following accepted and already published paper:

Lobera G, Besné P, Vericat D, López-Tarazón J, Tena A, Aristi I, Díez JR, Ibisate A, Larrañaga A, Elosegi A, Batalla RJ. 2015. Geomorphic status of regulated rivers in the Iberian Peninsula. Science of the Total Environment, 508: 101-114. *Impact factor (2015):* 3.976; *Area:* Environmental Sciences; *Quartile:* 1st.

Summary: In this chapter a new geomorphic status index is presented. This index was applied in 74 river sites distributed across four large Mediterranean basins in the Iberian Peninsula: Llobregat, Ebro, Júcar and Guadalquivir. The methodology used integrates climate and hydrological data, catchment scale information, ancient and contemporary aerial photographs and field data. Overall, results describe the degree of geomorphological alteration experienced by representative Iberian rivers mostly because of regulation, challenging the successful long-term implementation of river basin management programmes.

Key Words: geomorphic status, Iberian Peninsula, regulation, floods, morphology.

ABSTRACT

River regulation by dams modifies flow regimes, interrupts the transfer of sediment through channel networks, and alters downstream bed dynamics, altogether affecting channel form and processes. So far, most studies on the geomorphic impacts of dams are restricted to single rivers, or even single river stretches. In this paper we analyse the geomorphic status of 74 river sites distributed across four large basins in the Iberian Peninsula (i.e. 47 sites located downstream of dams). For this purpose, we combine field data with hydrological data available from water agencies, and analyse historical (1970) and current aerial photographs. In particular, we have developed a Geomorphic Status (GS) index that allows us to assess the physical structure of a given channel reach and its change through time. The GS encompasses a determination of changes in sedimentary units, sediment availability, bar stability and channel flow capacity. Sites are statistically grouped in four clusters based on contrasted physical and climate characteristics. Results emphasise that regulation changes river's flow regime with a generalized reduction of the magnitude and frequency of floods (thus flow competence). This, in addition to the decrease downstream sediment supply, results in the loss of active bars as they are encroached by vegetation, to the point that only reaches with little or no regulation maintain exposed sedimentary deposits. The GS of regulated river reaches is negatively correlated with magnitude of the impoundment (regulation). Heavily impacted reaches present channel stabilization and, in contrast to the hydrological response, the distance and number of tributaries do not reverse the geomorphic impact of the dams. Stabilization limits river dynamics and may contribute to the environmental degradation of the fluvial ecosystem. Overall, results describe the degree of geomorphological alteration experienced by representative Iberian rivers mostly because of regulation, challenging the successful long-term implementation of river basin management programmes.

1. INTRODUCTION

The form of an alluvial channel results from the interaction between water flow, sediment flux and basin landscape features, and it may change over time as a result of the continuous interplay between natural and human factors (e.g. Church, 2002; Rinaldi et al., 2013). Although channel forms such as gravel bars may appear stable, the grains of which it is composed are replaced regularly (i.e. annual flood) by new sediment from upstream. These fluvial processes are maintained in quasi-equilibrium through a spatial and temporal dynamic balance between water and sediment transport that promotes the creation and maintenance of habitats, and ensures ecosystems' integrity (Petts, 2000).

Rivers in Mediterranean regions are particularly affected by human impacts which modify hydrology, sediment fluxes, and channel forms at different scales. Dams stand out among these impacts, as they alter flow regimes, interrupt the sediment transfer, and subsequently change downstream erosion and deposition patterns (e.g. Brandt, 2000; Vericat and Batalla, 2006). Overall, the impacts of dams in dryland rivers tend to be more pronounced than those in more humid regions, since channel form and river ecology are adapted to highly variable flows (Gasith and Resh, 1999; Batalla et al., 2004). Following impoundment, the river undergoes a complex adjustment in channel shape that involves changes in width, depth, bed level, slope, bed material (i.e. grain size), bedforms and planform configuration (Brandt, 2000). As geomorphology is fundamental for river's ecosystem functioning, adjustments in physical habitat typically bring important effects for both the biota and ecosystem processes (Elosegi et al., 2010). Responses vary according to channel substrate and shape, flow regime, valley gradient, and the geophysical history (Merritt and Cooper, 2000). In particular, dams reduce high flows (hence flow competence and the associated physical disturbance), and often increase base flows (Batalla et al., 2004); altogether making these fragile environments more suitable for exotic species not adapted to marked hydrological cycles (Kondolf, 1997).

Owing to the highly variable and complex responses of river systems, most studies have been undertaken to simply examine the dam impact on a specific fluvial site (e.g. Surian, 1999; Gilvear, 2004; Vericat et al., 2006; Wyzga et al., 2012), whereas few studies cover broader spatial and temporal scales (e.g. Graf, 2006; Fitzhugh and Vogel, 2011; Batalla and Vericat, 2011). In parallel, indices have been developed to evaluate the physical river quality, mostly for restoration purposes (e.g. Raven et al., 1997; LAWA, 2000; Ollero et al., 2008; Rinaldi et al., 2013), all of them involving field work, and nearly all ignoring the temporal evolution of river channels. Nowadays, the high availability of data (e.g. hydrological data and aerial images) and the technologies for their analysis (i.e. GIS) provide new opportunities to make a more detailed analysis of the geomorphological changes over time, and also allow examining the current channel state in relation to pre-dam conditions (i.e. taken as reference conditions for the comparative analysis in this paper).

The main objective of this paper is to examine the effects of the dams on the channel geomorphology of 74 selected river reaches in the Iberian Peninsula. To accomplish this objective we present a methodology that integrates flow series and climate data, catchment scale information (i.e. GIS layers) and digital elevation models, ancient and contemporary aerial imagery, and field data. The study sites are first statistically classified (clustered) based on their climatic and hydrological characteristics (i.e. multivariate analysis). Subsequently, changes on the hydrological and flood regimes in each cluster are analysed with special emphasis to those reaches downstream from dams. The geomorphic status of study reaches is assessed by means of a novel Geomorphic Status (hereafter GS) index that is presented to evaluate channel's geomorphic activity; results are finally coupled and interpreted at the light of the hydrological changes, together with a discussion on the factors that most influence river channel activity.

2. STUDY SITES

We analyse a selection of river sites in four contrasting basins in the Iberian Peninsula (Fig. 1): Ebro (85,530 km^2), Llobregat (4,923 km^2), Júcar (21,632 km^2) and Guadalquivir (57,527 km^2). Catchments are mostly located in the Mediterranean region, altogether encompassing an extensive latitudinal, thermal, rainfall and hydrological gradient.

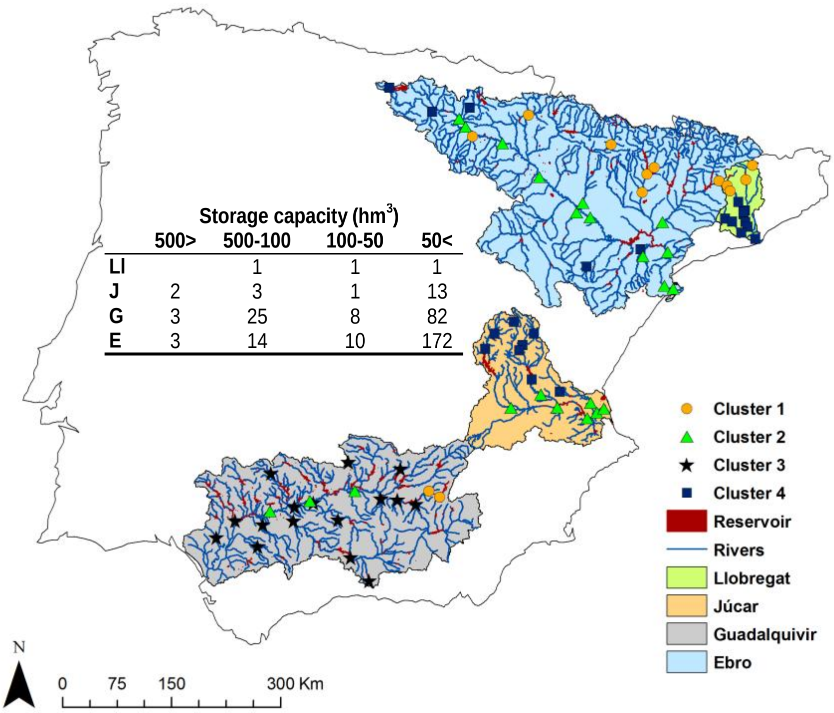

Figure 1. *The Iberian Peninsula with location of the study sites and reservoirs in each basin. The inset represents the number of reservoirs and their storage capacity for each of the basins. Sites are represented by symbols that indicate the physiographic and climatic cluster to which they belong (see Methods section for further information on clustering analysis).*

The basins are characterised by frequent periods of low discharge or even long dry periods during low-rainfall seasons, and flashy events during wet seasons (i.e. Mediterraneity), but with a very different recurrence and intensity (i.e. the degree of Mediterraneity varies between sites and basins). Mean annual precipitation at the basin-scale ranges from 520 to 700 mm, but it greatly varies regionally, from i.e. >2,000 mm in the Ebro headwaters to i.e. <300 mm in the Ebro Depression. In general, precipitation decreases on a north–south and west–east gradient. An extensive network of dams for hydropower and irrigation purposes have been built in the region, starting in the late 19th century, accounting for a considerable impoundment capacity (to express it we use the Impoundment Ratio — IR, defined as the ratio between the reservoir storage volume and the mean annual runoff expressed in percentage, as per Batalla et al. (2004)).There are 187 large dams in the Ebro basin (reservoir storage volume V = 8,022 hm^3, i.e.1 hm^3 =1 × 10^6 m^3, mean IR = 0.6 i.e. 60%), 118 in the Guadalquivir (V = 8,192 hm^3,IR = 1), 19 in the Júcar (V = 2,741 hm^3, IR = 2.2), and 3 in the Llobregat (V = 223 hm^3, IR = 0.46). Dams typically alter flood frequency and magnitude, and subsequently channels react by reducing their morphological complexity (the presence of river forms) and activity (sediment mobility that, in turn, affects river forms). For this study, a total of 74 study sites were selected from 36 rivers representing small, medium and large basins (i.e. 24 sites in the Ebro, 14 in the Llobregat, 15 in the Júcar and 21 in the Guadalquivir). A total of 47 sites are located downstream from dams (i.e. thus considered regulated), with the rest not regulated (Fig. 1). Regulated sites are 4 km to more than 100 km downstream from dams. The capacity of the reservoirs included in this study span several orders of magnitude, from 1 to more than 1,000 hm^3. Data base has been fragmented in order to address each of the objectives and the corresponding analysis.

3. METHODS

Data base includes information of 74 study sites (see location in Fig. 1). Data have been fragmented according to the different analyses (i.e. Fig. 2 exemplifies how data is fragmented): a) classification (or clustering) based on their physiographic and climatic characteristics (i.e. multivariate analysis); b) analysis of the hydrological differences between sites within each group; c) assessment of the geomorphic situation of the sites by means of the Geomorphic Status (GS) index; and, finally, d) examination of the relation between the current river's geomorphic status and the hydrological alterations caused by regulation. Following, we present a brief description of each of the analysis (see Fig. 2 for a complete view of data fragmentation and analysis):

a) Classification (clustering): For this analysis all sites were used (n = 74). The multivariate analysis provides the number of statistically significant clusters based on physiographic and climatic characteristics.

b) Hydrological regime: A total of 46 sites provide the required data to perform the analysis (see details of the indices used to measure hydrological alteration in the next sections). Of the total, 30 sites are located downstream from dams and 16 are located in rivers not regulated.

c) Channel morphology: A total of 42 sites provide the required data to perform the geomorphic analysis (see details on the GS in the next sections); of them, 31 sites are located downstream from dams and 11 are located in not regulated rivers.

d) Effects of regulation on the geomorphic activity: This analysis is performed only for the sites located downstream from dams where hydrological information and GS could be coupled. A total of 19 river stretches were considered for this part of the analysis.

In the following sections, we first describe in detail the different components of the data base and introduce the main variables that were calculated. Secondly, we provide details on how data analyses were performed and, finally, we present the Geomorphic Status (GS) index, an indicator specifically developed here to assess the geomorphic status of regulated river reaches.

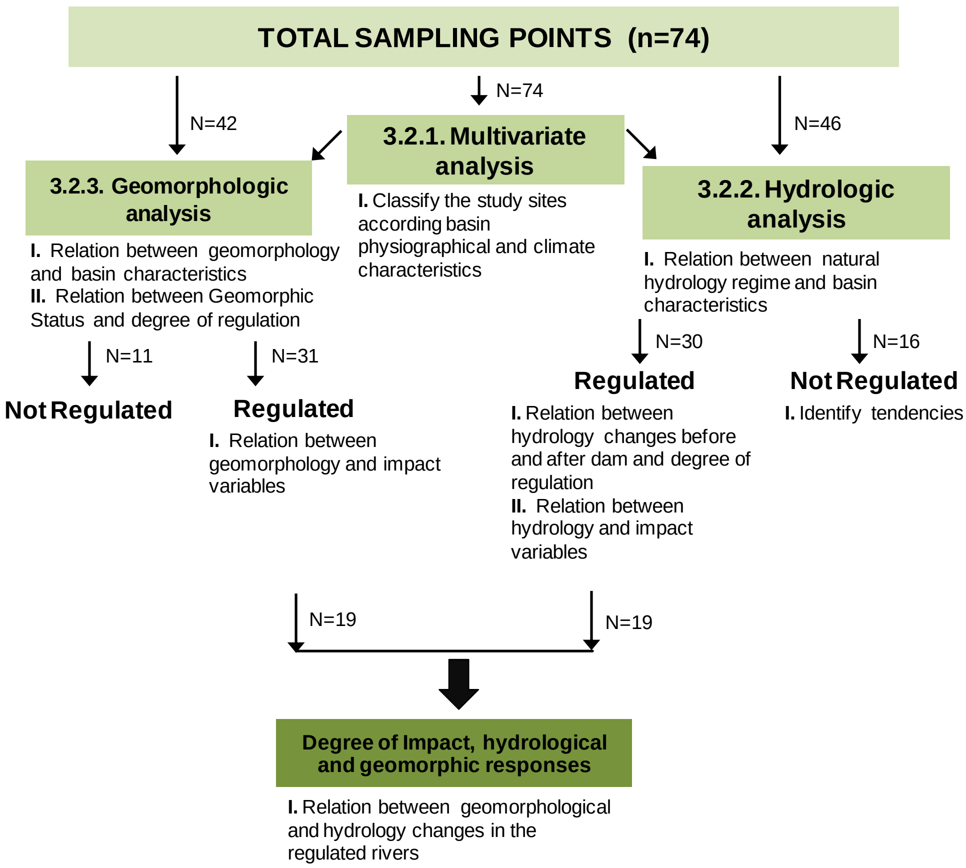

Figure 2. *Workflow summary for the hydrologic and the geomorphic analysis. Note that the main sets of analyses are indicated together with the objectives, the number of sites used in each analysis and the main outcomes (see text in Section 3.3 for more details).*

3.1. Data compilation and fragmentation and extraction of variables

Table 1 summarizes the main variables calculated from the six components of the data base i.e. five components are based on archival information (e.g. flow series, aerial photos), in addition to the direct field observations on the current river morphology specifically undertaken for this study.

3.1.1. Physiographic variables (catchment)

Catchments upstream from each site were characterised using ESRI® ArcMap™ 9.3 (Table 1). The spatial analysis was based on a digital elevation model (DEM) with a cell size ranging from 20 × 20 to 30 × 30 m. ESRI Spatial Analyst® was used to process each DEM and delineate the drainage area (A), the stream network (L) and the stream order (SO) following Strahler's classification in each site. ESRI 3D Analyst Tools® were used to define the mean basin slope (Sb). The Gravelius index (K_G) was also calculated to represent the basin shape, as this may influence the hydrological response (see Table 1 for definition). Geology of the catchments was described with the average Rock Resistance Class value (RRC; as per Clayton and Shamoon, 1998), re-drawn and estimated from the 1:1,000,000 Geological Map of the Iberian Peninsula (Spanish Geological and Mining Institute — IGME). This index classifies lithologies in 6 classes according to their resistance to erosion (i.e. 1 very weak to 6 very resistant).

3.1.2. Climatic variables (catchment)

Monthly precipitation and evapotranspiration data from the period 1950–2009 were obtained from the SIA (Integrated Water information System, Spanish Ministry of Agriculture, Food and Environment; for more information see www.magrama.gob.es). Data are provided in raster format of 1 × 1 km pixel resolution. From the raw data several climatic variables were elaborated (see Table 1 for details): (1) mean annual precipitation (Pm), (2) Aridity Index (AI), here simply taken as the ratio between mean annual precipitation and mean annual evapotranspiration and, (3) the coefficient of variation between monthly precipitation means (MC); the last expresses the variability between months and reflects the degree of Mediterraneity of a given site. All variables were derived using ESRI ArcMap® 9.3 from the digital rasters.

3.1.3. Hydrological variables (at-a-site)

Hydrological data were obtained from daily streamflow series compiled from various water agencies in Spain, namely the Catalan Water Agency — ACA, the Hydrographic Studies Center — CEDEX, and the Automatic Hydrological Information System — SAIH. Hydrological responses through time were analysed for both the regulated and the non-regulated sites.

The analyses of the effects of dams on river's hydrology were limited to the sites where pre-dam data was available (n = 30) that presents series varying from 6 years to 83, with an average of 33 years per series. We are aware that there are some limitations associated to length of the flow series, thus this may have a certain influence on the final results; however, given the intrinsic nature of the study (large catchments on a broad scale) we believe that the general patterns described in the paper will remain very similar and that the final effect of the time series length shall be considered as minor. Daily flows were analysed using the Indicators of Hydrologic Alteration (IHA) software (Richter et al., 1996; Mathews and Richter, 2007) that produces more than 30 variables, from which we selected four (1-day maximum flow, number of high flow pulses, number of low flow pulses and number of reversals; see Table 1 for notations and definitions) because of their relevance for channel geomorphology (Graf, 2006). In addition, three more variables (i.e. discharges corresponding to a return period of 2, 10 and 25 years, calculated by means of the Extreme Gumbel Value distribution) and added to complete the analyses (Table 1). All variables were calculated for the pre- and post-dam records. The ratio between post- and pre-dam records indicates the effect of regulation on each hydrological variable.

Additionally, hydrological data of not regulated sites was analysed in order to study the existence of changes that suggest a response to other environmental pressures (either natural or human-induced), such as changes in land use, increase in water demand, or climate change. Of the 27 not regulated sites, only 16 presented suitable enough data for the analysis (i.e. flow series had a length between 22 and 96 years). Series were also analysed by means of IHA, although in this case we worked data records as a whole, looking for temporal trends from linear regression for each variable over time. Finally, basin torrentiality, taken as a proxy of the Mediterraneity character of the basin, was also calculated for both regulated and not regulated river reaches; torrentiality is represented by the ratio between the mean of the maximum discharges in the series (annual instantaneous maximum — Q_{ci} or annual daily maximum — Q_c depending on data availability) and the mean discharge (Q_n).

Table 1.
Basin and stream reach characteristics used to define study sites and analyse the impact of regulation.

Component / Variables	Definition
Physical	
Drainage area (A, km^2)	Area drained by the river (study point) and its tributaries
Channel length (L, km)	Length of the main river and their tributaries
Mean basin slope (Sb, %)	Mean slope of the drainage area
Gravelius index (K_G)	Basin area divided by the corresponding catchment perimeter
Stream Order (SO)	Stream Order by Strahler (1957)
Rock Resistance Class (RRC)	Classification according to resistance to the erosion
Climate	
Mean annual precipitation (Pm in mm)	Mean annual precipitation of the drainage area
Monthly variation coefficient (MC in %)	Variation between mean month precipitation
Aridity Index (AI)	Quotient between ETP and precipitation
Hydrological	
Q_a	Day mean annual flow
Q_2, Q_{10} and Q_{25}	Return period of 2, 10 and 25 years
1 day maximum flow (DMF)	Mean of the highest single daily value each year
Base Flow Index (BFI)	7-day minimum flow divided by the average annual flow
Number of low flow pulses (NLF)[1]	Mean of the number of low flow pulses each year
Number of high flow pulses (NHF)[2]	Mean of the number of high flow pulses each year
Number of reversals (NR)	Mean of the number of flow variation between consecutive days
Torrentiality	Mean maximum discharge between mean discharge
Geomorphic	
Active bars (NA)	Number of active bars
Vegetated bars (NV)	Number of vegetated bars
Total bars (NB)	Number of total bars
Channel width (W)	Mean of active channel width of the stream reach
Dam impact	
Distance (D_r)	Distance to the dam from the study site
Reach Impoundment Ratio (IR_r)	Impoundment ratio according to the upstream reservoir
Total Impoundment Ratio (IR_t)	Impoundment ratio according to the sum of reservoirs
Tributaries	Number of tributaries to the dam from the study site
Field –based	
Hydraulic geometry ratios	Mean and maximum depth divided by channel width
Shear Stress	Calculated following the DuBoys approach
Armouring	Ratio between median surface and subsurface bed-material

[1] Low pulse defined as the 25th flow percentile of the flow frequency distribution (as per Richter et al., 1996)
[2] High pulse defined as the 75th flow percentile of the flow frequency distribution (as per Richter et al., 1996)

3.1.4. Geomorphic variables

A series of geomorphic variables were calculated and compared from two sets of aerial photographs i.e. 1970s and the current (2011). It should be noted that geomorphic variables provide a general evaluation of the at-a-moment channel activity, as we do not aim for a detailed characterisation of channel evolution. Images from the late 1970s, freely available at National Geographical Institute — IGN web site (www.ign.

es), were taken as the *reference* image i.e. most dams in Spain were built between 1960 and 1970s and we considered the geomorphology of the river reaches downstream from the dams not yet severely affected. The current images were also obtained through the IGN web site by using the 'Iberpix Viewer'.

In order to extract the variables across a representative reach, we defined the optimal channel length as the one that equals 20 times the width of the active channel (following Walter and Tullos, 2010 criteria). Four variables were extracted in both set of images (Fig. 3; Table 1): (1) number of active lateral and point bars (NA), taken as potential unstable features that are frequently inundated during high flows; (2) number of vegetated bars (NV) (i.e. >50% of the bar area is covered by vegetation), that are relatively stable forms only inundated during larger floods; (3) total number of bars (NB); and (4) mean active channel width (W) calculated from 10–20 transects (depending on the river size) along the main channel. It is worth to mention that these variables have a different character than the ones that can be obtained by spatial disaggregation and aggregation procedures as, for instant, those described by Alber and Piégay (2011). Such approaches are used to support and automate large-scale characterisation of fluvial systems, while the objective of this paper is to obtain local variables that provide information about the geomorphic status of different river reaches located in different catchments at a given moment.

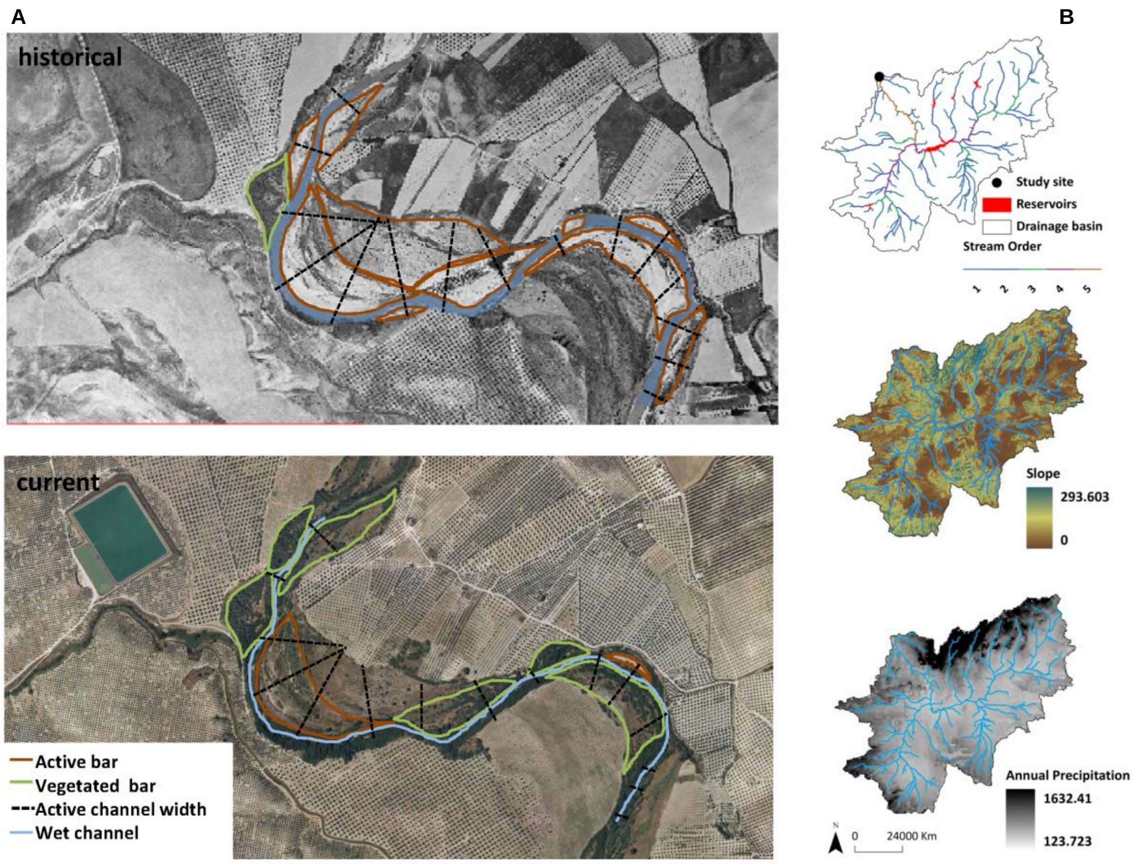

Figure 3. *(A) Example of mapping of sediment units (active and vegetated bars) and active channel width transects along a reach, illustrated by two images (historical and current) of a reach of the River Guadiana Menor (i.e. GUAM, Guadalquivir basin). (B) Maps of the GUAM drainage basin that show some of the physical (stream order and slope) and climate (mean annual precipitation) variables that have been used for the cluster classification.*

3.1.5. Impact variables

To estimate the degree of hydrological impact affecting each site and to assess the influence of regulation on river morphology, we used the Impoundment Ratio (IR). In our case, two IRs were calculated (Table 1): 1) reach IR (IR_r) that relates to the closest reservoir located upstream of the study site and, 2) total IR (IR_t) that relates to the impoundment capacity of all reservoirs located upstream from the study site. Reservoir capacity and mean annual runoff were obtained from water agencies. Mean annual runoff of sites where official flow records are not available was obtained from the CEDEX-SIMPA Rainfall– Runoff Integrated Modelling System. Finally, the distance from the dam to the study site and the number of tributaries between the dam and the site were also calculated (Table 1). Only the tributaries with a stream order equal or higher to half of that of the study site were taken into consideration; the role of smaller tributaries on the mainstream river flow and channel forms was considered negligible.

3.1.6. Field-based variables

Data base was completed with ad-hoc field data obtained in 2010 and 2011. All the 74 study sites were surveyed, although not all of them were suitable to obtain the complete set of variables (i.e. sediments not exposed, too deep for wading, etc.); 26 sites were finally analysed (Table 7). Channel slope were measured by means of a Geodimeter® 422 Total Station and a Leica® TCRP1201 Robotic Total Station. To characterise surface sediments on the river bed, the *b* axis of a minimum of 100 particles was measured using a gravel template with squared holes at 1/2 ϕ unit classes (particles finer than 8 mm were not included, as per Wolman (1954)). Particles were sampled in open bars at sedimentologically equivalent positions, typically bar head to avoid downstream fining (Rice and Church, 1998). Subsurface material was sampled in the same exposed bars using the volumetric method (Church et al., 1987), i.e. a representative patch of the bar (typically of 1 m^2) was spray-painted to differentiate the surface from the subsurface material (Lane and Carlson, 1953), the volume of the subsurface sample determined based on the weight of the largest particle (the weight of the largest particle never represented more than 1% of the total sample, as per Church et al. (1987) criteria in gravel-bed rivers). Subsurface materials were extracted and transported to the laboratory where they were dried and sieved for a later size-class classification according to the Wentworth scale.

Finally, current channel activity was characterised by combining topographical surveys with surface sediment data. This way, channel potential activity is characterised from shear stress (calculated following the DuBoys approach) at bankfull stage, and riverbed armouring (ratio between median surface and median subsurface bed-materials from grain-size distributions) (see Results and Discussion section and Table 7 for complete data).

3.2. Assessment of the Geomorphic Status of regulated rivers

An index to assess the Geomorphic Status (GS) and the degree of change of each regulated site was developed based on the variables extracted in the geomorphic component of the data base (Table 1). The GS includes four dimensionless indices:

1. Changes in Sedimentary Units (SU). It represents the difference in the geomorphic complexity of the river reach. SU is calculated as:

$$SU = [\ (1+(NB/L)_{post})\ ]\ /\ [\ (1+(NB/L)_{pre})\ ]$$

where *NB* is the number of bars, *L* is channel length (km) and *pre* and *post* refer to the reference and current images, respectively. A result of 1 implies no change, whereas values >1 or <1 indicate an increase or decrease, respectively, of the number of sedimentary units.

2. Changes in Sediment Availability (SA). It indicates the river dynamism and the

availability of sediment coming from upstream, and it is represented by the degree of bar activity. If NB_{post} is 0 then *SA* must be 0 (if no bars are exposed we consider that sediment availability is negligible in the reach); in contrast, if NB_{post} is > 0 then SA can be calculated as follows:

$$SA = [\ (1+(NA/NB)_{post})\ ] \ /\ [\ (1+(NA/NB)_{pre})\ ]$$

where *NA* is the number of active bars. If results equal 1 there have not been major changes in sediment availability, whereas values >1 imply an increase on sediment deposition and <1 a reduction of sediment availability.

3. Changes in Bar Stability (BS). The presence of vegetation in bars is an indicator of stability. BS evaluates the difference in vegetation cover through time, thus complementing SA. As in the previous case, if NB_{post} is 0 then BS must be 0; but, if NB_{post} is > 0 then *BS* can be calculated as:

$$BS = [\ (1+(NV/NB)_{pre})\ ] \ /\ [\ (1+(NV/NB)_{post})\ ]$$

where *NV* is the number of vegetated bars and *pre* and *post* refer to the reference and current images, respectively. A bar has been considered as vegetated when >50% of its area is covered by vegetation. Values >1 imply a reduction of the vegetation cover and <1 an increase of the number of vegetated bars over time.

4. Changes in Channel Flow (CF) capacity. This index evaluates the variation on the active channel width, which relates mainly with changes in the frequency and magnitude of flood events. CF is calculated by means of:

$$CF = W_{post} \ /\ W_{pre}$$

where *W* is the mean width of the active channel (in m) in the reach, and *pre* and *post* refer to the reference and current images, respectively. Values >1 imply an increase on the active width, suggesting an increase of the frequency and magnitude of competent events.

GS is calculated as the sum of the previous indices (i.e. GS = SU + SA + BS + CF). A GS equal or close to 4 implies an overall maintenance on the geomorphic characteristics of the reach, whereas values >4 would indicate an increment of the geomorphological activity in the reach, and values <4 would suggest a tendency towards channel stabilization or degradation (i.e. loss of geomorphic diversity, simplification of the channel pattern, disappearance of sedimentary active areas, together with bed armouring and incision). It is worth to mention than the applicability of this index is limited to the characteristics of the river reach (e.g. channel width, presence of expose bars) and to the availability of appropriate aerials (e.g. scale, flow conditions) that allow calculating the necessary variables.

3.3. Data analysis

(1) Multivariate analysis (clustering)

Study sites were first classified into homogeneous subregions according to their basin physical (drainage basin area, mean basin slope, Gravelius index, rock resistance, channel length and stream order) and climatic (Pm, AI and MC) variables (Table 1). To this end, a Spearman correlation matrix was used to detect redundancy among these variables. Next, Principal Components Analysis (PCA) was applied to assess the weight of each of remaining variable (i.e. for instance, rock resistance that was lately eliminated due to its low significance). Finally, the five remaining variables were used to create homogeneous subregions after applying the *k*-means clustering method by means of StatSoft STATISTICA® 7.0. In order to define the number of clusters, two techniques were used: (1) V-fold cross-validation for which repeated random samples are drawn from the data for the analysis and the respective model is then applied to compute predictive classification; and (2) trial and error approach to select the most appropriated number of clusters which adjust to an ANOVA criterion for a significant level $p<0.001$ (Fang et al., 2012). Once sites were classified into statistically significant clusters, one-way ANOVA was conducted to determine which variables are the main responsible to differentiate the groups. Additionally, Tukey post-hoc test was also applied to define where differences are related to the existence of three or more groups.

(2) Hydrological analysis

The second set of analyses is performed to examine the influence of physical and climatic conditions on river hydrology. As stated, hydrological data were available for 46 sites (30 regulated and 16 not regulated). Natural conditions (before dam construction) were assessed by calculating the median and the first and third quartiles (i.e. quantiles 25th and 75th) of each of the hydrological variables for each cluster. Subsequently, the degree of change for both regulated and non-regulated reaches was examined. In the first case, the change due to the regulation was calculated by means of the ratio between post-dam and pre-dam values of variables. In this way, a value >1 represents an increase of the magnitude of the variable analysed. In relation to the non-regulated sites, the hydrological response was evaluated by means of linear regressions.

(3) Geomorphological analysis

The hydrological analyses were followed by geomorphological analyses. We assessed the differences between the *reference* (i.e., end of 1970s) and the *current* (i.e., 2011) channel geomorphology at each study site. Morphological variables (Table 1) were examined at each of the 74 study sites; although 20 of them did not show any visible geomorphological structure (i.e. bars) already in the reference image. In addition, 12 sites were also excluded because either they were too small or the riparian vegetation precluded any correct measurement of the river channel. Thereby, analyses were finally carried out for 42 reaches. The remaining sites were subsequently grouped after the clusters previously established to examine the degree of influence of physiographic and climatic conditions on channel morphology. After this classification, median and selected quartiles of each geomorphic variable both for the reference and the current conditions were calculated. A multiple regression model was applied to derive statistical relations between dam impact parameters (as independent variables) and both hydrologic and geomorphic parameters (as dependent variables). Finally, the relation between hydrological and geomorphological responses is established in rivers affected by regulation.

4. RESULTS AND DISCUSSION

4.1. Site classification in relation to physiographic and climatic variables

The Spearman correlation test indicates that stream length (L), stream order (SO) and aridity (AI) had to be excluded because they are redundant ($r > 0.9$, $p < 0.05$) with drainage basin area (i.e. L and SO) and mean annual precipitation (i.e. AI), respectively. The first two factorial axes in the PCA explained 71.5% of the variance; owing to this analysis we also eliminated the Rock Resistance Class (RRC) because it explains <0.01 of the variance for the first two axes. The rest of the variables (drainage basin area, mean basin slope, Gravelius index (see Table 1 for definition), mean annual precipitation and monthly variation coefficient) were taken for the next step. The subsequent V-fold cross validation and trial and error approach grouped the study sites into four climatic and physiographic subregions (Fig. 4). The one-way ANOVA reveals a significant difference ($p < 0.05$) between the descriptive variables of the clusters. However, the Tukey post-hoc test indicates that not all variables present significant differences ($p < 0.05$) between clusters. The final cluster and the variables that allow distinguishing one to the other are defined as follows:

- Cluster #1 (13 sites) grouped river sites with high mean basin slope and high annual precipitation, characteristics typical of headwater rivers;

- Cluster #2 (22 sites) grouped reaches with large drainage areas and high Gravelius index (i.e. elongated basin shape), which were located in lower-most parts of the Ebro, Júcar and Guadalquivir basins;

- Cluster #3 (16 sites) grouped reaches in the Guadalquivir basin characterised by a high degree of Mediterraneity and low annual precipitation; and

- Cluster #4 (23 sites) encompasses a mixture of reaches with no characteristically different features, and includes the majority of the study sites in the Llobregat and the Júcar basins.

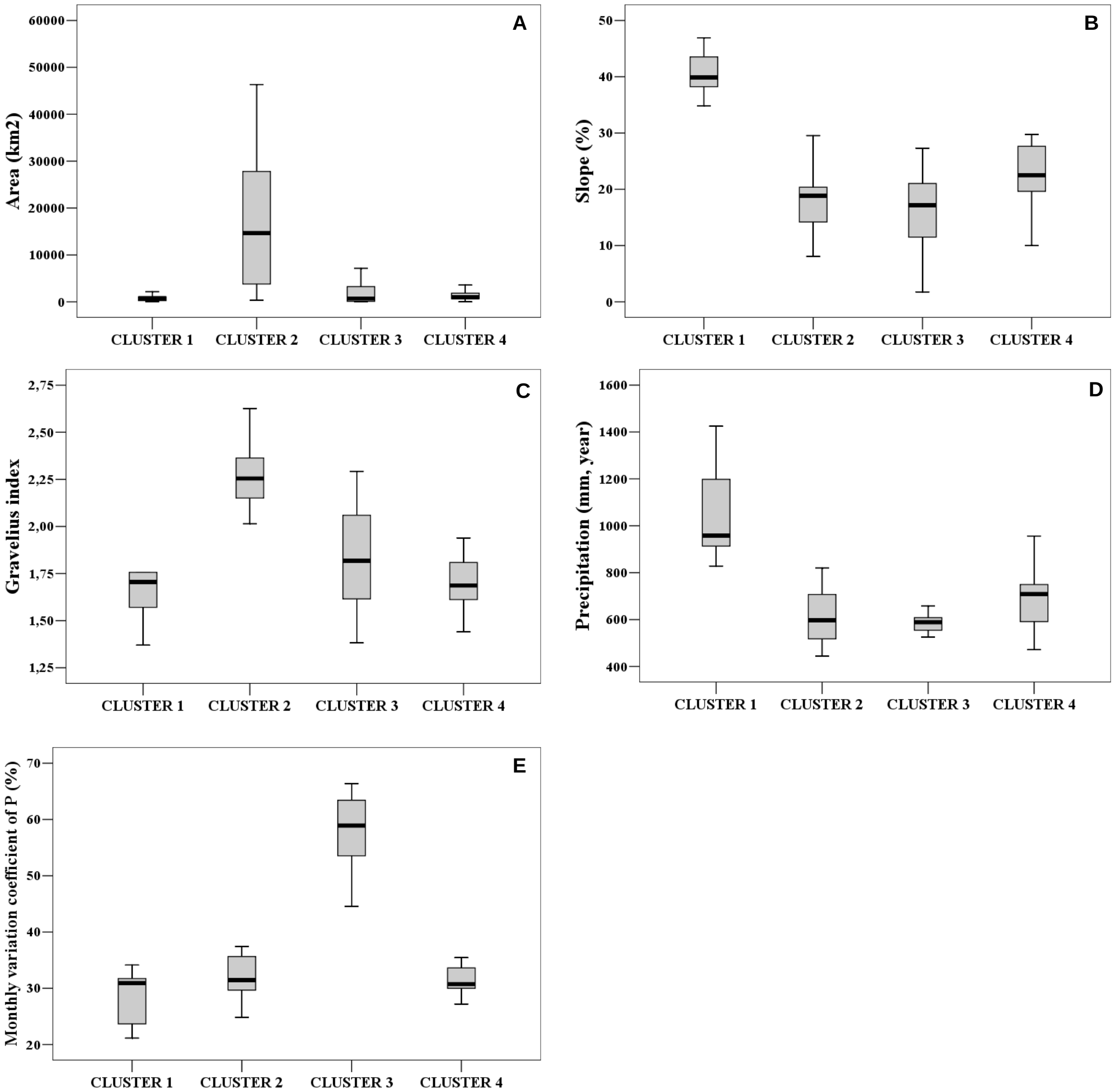

Figure 4. *Box plots of the climatic and physiographical characteristics for each cluster: (A) drainage area (km^2), (B) mean basin slope (%), (C) Gravelius index, (D) mean annual precipitation (mm), (E) monthly variation coefficient of precipitation (%).*

4.2. Hydrological responses in regulated and non-regulated rivers

In regulated rivers (30 sites), the annual streamflow and the magnitude and frequency of floods showed a generalized decrease (Fig. 5). This decrease is especially remarkable for the high-frequency and low-magnitude events (i.e. DMF and Q_2). Conversely, the frequency of low discharges and the number of reversals increased (see Table 1 for definitions). This increment may be due to particular dam operations, such as particular releases for water supply (Graf, 2006). Hydrological variables related to flow magnitude (DMF, Q_2, Q_{10} and Q_{25}) were negatively correlated with the degree of regulation and positively with the number of tributaries (Table 2). This fact indicates that the impacts of dams are attenuated downstream in relation to tributary inflows. In addition, the hydrological variables related to frequency of hydrological events (NLF, NHF and NR) tend to increase below dams in sites with low regulation, in some tributaries and in sites located far from the reservoir.

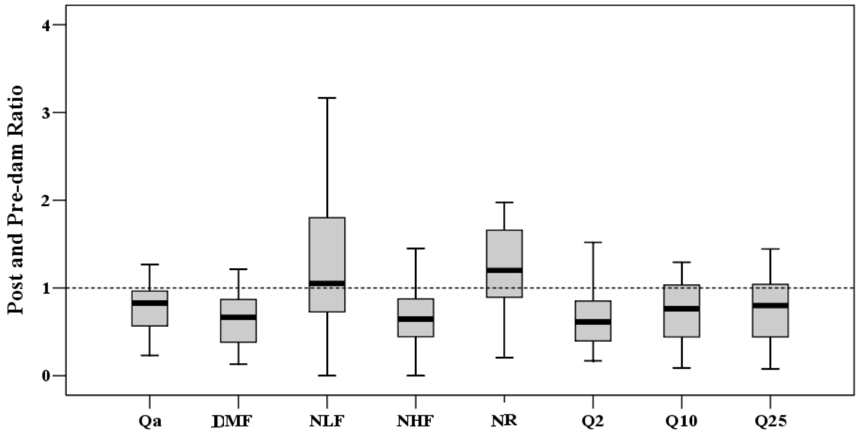

Figure 5. *Box plots of the quotient between post-dam and pre-dam for each hydrological variable (as per Richter et al. (1996); see Table 1 for details) (Q_a: daily mean annual flow, DMF: 1-day maximum flow, NLF: number of low flow pulses, NHF: number of high flow pulses, NR: number of reversals, flood with 2, 10 and 25 years of return period, respectively). Horizontal dotted line indicates no change, <1 imply a reduction and >1 imply an increase, between post-dam and pre-dam periods. The medians (central bar), 25th–75th quantiles (box) and non-outlier range (whiskers) are shown in the plot (for clarity outliers not shown).*

Table 2
Multiple regression between hydrologic variables (§ indicates the ratio between post and pre-dam values) and degree of regulation (IR_r), number of tributaries and distance to the dam (statistically significant at 0.05 and +significant at 0.1 confidence level).*

	IR_r	**No. of tributaries**	**Distance (km)**
§Q_a[1]	-0.28	0.09	0.16
§DMF[2]	-0.50*	0.12	-0.03
§NLF[3]	-0.40*	-0.34	0.35
§NHF[4]	-0.31	-0.40	0.55*
§NR[5]	-0.44*	-0.43[+]	0.63*
§Q_2[a]	-0.44*	0.47*	-0.26
§Q_{10}[a]	-0.30	0.35	-0.26
§Q_{25}[a]	-0.29	0.34	-0.25

[1] *Daily mean annual flow (as per Richter et al., 1996; see table 1 for definition)*
[2] *1-day maximum flow*
[3] *Number of low flow pulses*
[4] *Number of high flow pulses*
[5] *Number of reversals*
[a] *Flood with 2, 10 and 25 years of return period, respectively*

In turn, not regulated rivers (16 sites) present more heterogeneous responses i.e. not all sites have significant changes in the frequency and magnitude of annual floods (as per Richter et al. (1996), see Table 1 for notations and definitions) during the period with historic records (Table 3).

Table 3
*Temporal trend (expressed and the slope of the linear function) of each hydrological variable in the not regulated sites with more than 20 years of data available (values highlighted with * means that correlations are significant at 0.05 confidence level).*

	Site	DMF[1]	NLF[2]	NHF[3]	NR[4]
Ebro	OCA	-0.427	-0.036	-0.038	-0.378
	MAT	1.491	0.190*	-0.235*	-0.608
	MAR	-0.006	0.085*	-0.021	0.623*
	EBR1	-0.336*	0.109*	0.011	0.320
	ALG	0.769	0.045	0.009	0.911*
Llobregat	LLO1	-0.031	0.229*	-0.069	1.683*
	ANO1	-0.148*	0.043*	-0.056*	0.032
	ANO3	-0.719*	0.301*	0.187*	2.838*
Júcar	CAB2	-0.333	-0.011	-0.071*	-0.624*
	CAB3	-0.453	-0.309	-0.404*	-1.443*
	JUC1	-0.204	-0.104	0.077	-0.515
Guadalquivir	GEN1	-0.466	0.024	-0.030	0.614*
	GUAN	-0.759*	0.060*	-0.025	-0.531*
	YEG	-3.413	0.025	-0.033	2.204*
	GUAA	0.659	-0.055	-0.068	1.225
	GUAR	3.312*	0.060	0.326*	2.137*

[1] 1-day maximum flow (as per Richter et al., 1996; see table 1 for definition)
[2] Number of low flow pulses
[3] Number of high flow pulses
[4] Number of reversals

Frequency of low pulses (NLF) increased at 7 sites and did not change at 9, the frequency of high pulses (NHF) increased at 2 sites, decreased at 4 and did not change at 10, whereas the number of reversals (NR) increased at 6 sites, decreased at 3 and did not change at 7. Otherwise, the magnitude of annual floods (DMF) increased in 1 site, decreased in 4, and did not change in 11. Hydrological changes in rivers not affected by dams may reflect the influence of other factors such as climate variability, land uses changes and water abstractions (Arora and Boer, 2001; Lorenzo-Lacruz et al. 2012; Rinaldi et al., 2013). For instance, a recent study of 187 river basins in the Iberian Peninsula (Lorenzo-Lacruz et al., 2012) showed a generalized decrease of annual flow, corroborating previous findings by Gallart and Llorens (2004). This tendency is generally related to the pattern of decreasing precipitation found in the Mediterranean basin (Xoplaki et al., 2004), but also with an increase of the forested land and an expansion of the irrigated surface. The increase of the evapotranspiration caused by the abandonment of cultivated fields and its replacement by shrubs and forests (Hill et al., 2008) together with the increment of the temperature (Chaouche et al., 2010), result in a reduction of the runoff generation in the headwaters (most of the not regulated rivers in this paper are located in headwaters). Thus, land use seems to have lesser influence on them than on average runoff. Three sites showing a negative pattern (CAB2, CAB3 and ANO1) have suffered a significant increase in forest and natural vegetation cover (Gallart et al., 2011; Herráiz-Hernansanz and Serrano-Gil, 2013). These results are consistent with those obtained by López-Moreno et al. (2006), who showed a general decrease in flood intensity despite no change in the frequency and distribution of the precipitation in the central Spanish Pyrenees. Altogether, results fit with the pattern described in the IPCC, 2007 for the Mediterranean region, which reported an increase in heavy precipitation events that causes an increase of flooding, but a decrease in total runoff that reduces mean and minimum flows.

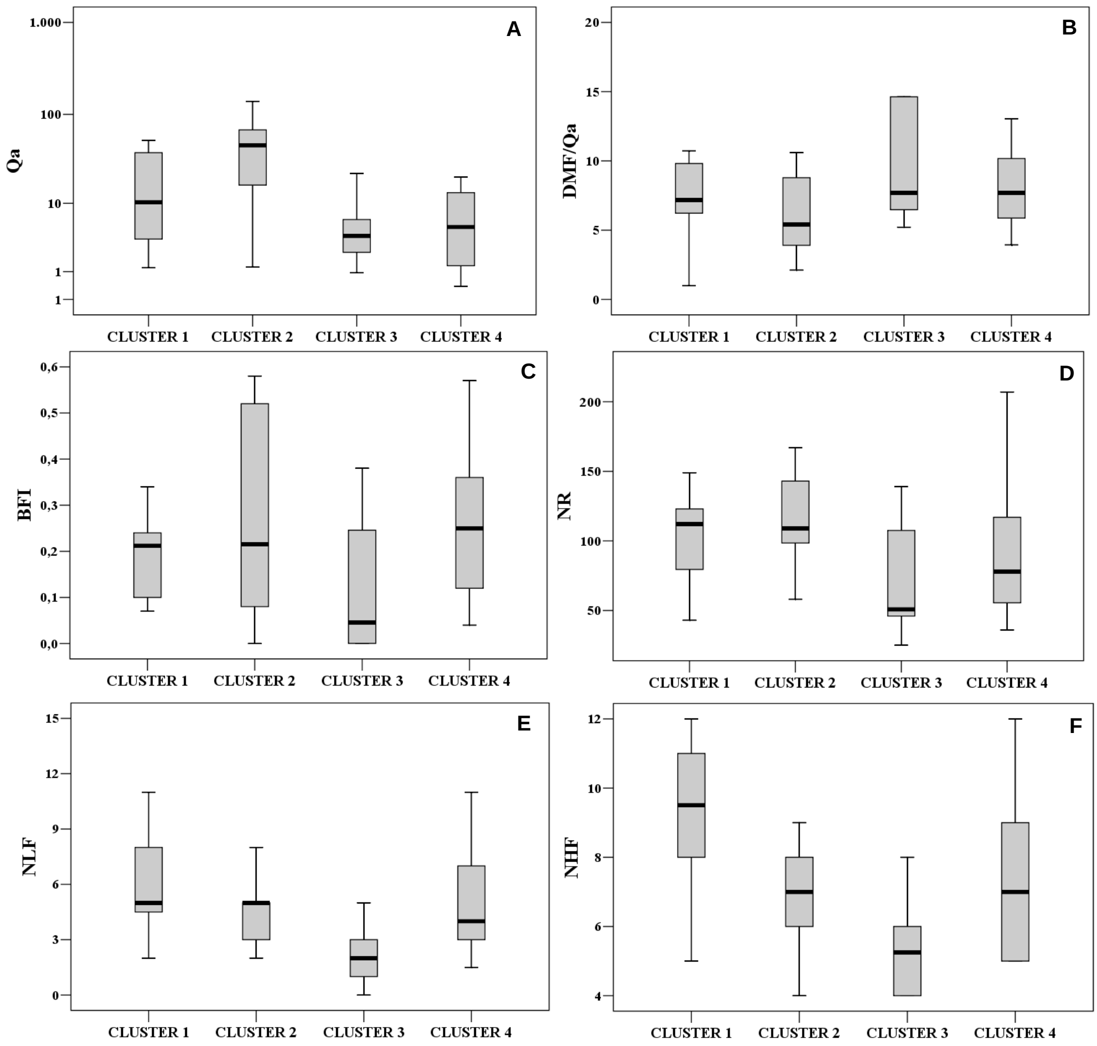

Figure 6. *Box plots of analysed hydrological variables (as per Richter et al. (1996); see Table 1 for details). (A)Q_a: daily mean annual flow, (B) DMF/Q_a: 1-day maximum flow divided by daily mean annual flow, (C) BFI: base flow index, (D) NR: number of reversals, (E) NLF: number of low flow pulses, (F) NHF: number of high flow pulses. The medians (central bar), 25th–75th quantiles (box) and non-outlier range (whiskers) are shown in the plot (outliers not shown).*

Results show that hydrological responses differed between river clusters (Fig. 6). Headwater sites (Cluster #1) were characterised by frequent pulses of high and low flow. In contrast, lower reaches (Cluster #2) exhibit higher mean daily flow and higher number of reversals. Mediterranean sites (Cluster #3) showed minimum base flow (i.e. ephemeral rivers), the largest 1-day maximum flow and minimum number of low and high flow pulses. Finally, sites in Cluster #4 showed intermediate behaviour but higher recurrence of high and low pulses.

4.3. Geomorphological response to river regulation

Fig. 7 shows the number of active (NA) and vegetated (NV) bars (expressed in percentage) in relation to the local impounded ration (IR_r) for the reference and contemporary periods. In the late 1970s most sites presented an elevated percentage of active bars (Fig. 7A) with a median of 59% of active bars over the total number of bars for all the sites. This pattern suggests that although impoundment was present in some of the analysed river reaches, river channels are still active because the time since dam construction was still too short and probably below the required reaction time needed for the effects being observable.

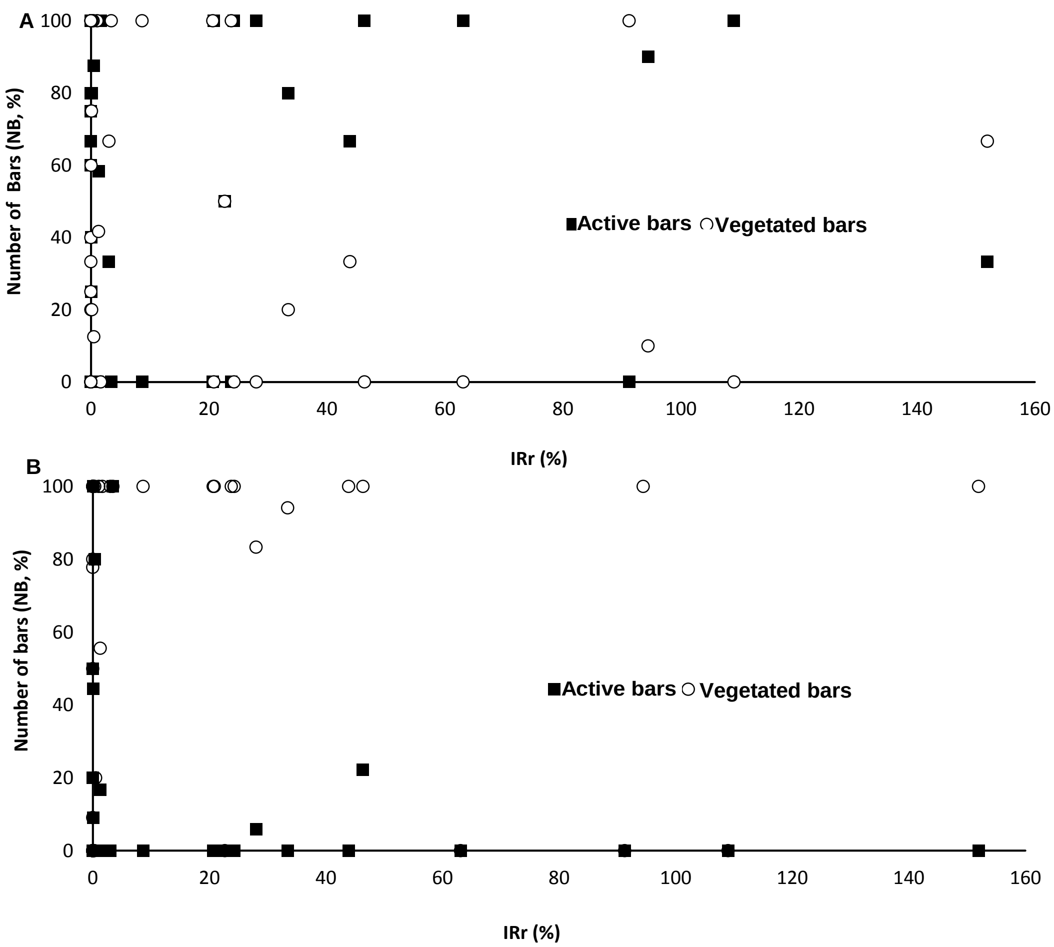

Figure 7. *Percentage of active and vegetated bars for each site in relation to the degree of regulation (local Impoundment Ratio—IR_r; see Section 3.1 in the text for reference) in the reference image (A) and the current situation (B).*

The pattern reverses when the current situation is analysed (Fig. 7B). Currently, most bars have been encroached by vegetation, and only sites with little or no regulation maintain exposed bars i.e. the median percentage of vegetated bars reaches nowadays 97%. During periods of relatively small floods, riparian vegetation is able to colonize fresh gravel deposits, leading to the conversion of active channel bars to relict deposits and floodplain (Nelson et al., 2013). The stabilization limits river dynamics and contributes to the environmental degradation of the fluvial ecosystem (Ollero, 2010; Magdaleno et al., 2012), thus reducing the habitat for aquatic and riparian wildlife (Graf, 2006).

The GS of the 42 study sites (Fig. 8) was negatively correlated to IR_r, but not to IR_t (Table 4, Fig. 8), thus showing that the effect of the local regulation is more important than that of the total basin; a dam located immediately upstream from a study reach controls the flow regime and the sediment trapping (bedload) directly affects the reach; whereas the effects of other dams located further upstream are presumably more diffuse. The hydrological effects of dams propagate further downstream too, and their effects on sediment movement and the sediment budgets (thus channel form) tend to recover (although never completely) as the river merges with sedimentary active tributaries. Distance for partial recovery of sediment load and channel activity (i.e. looseness of surface gravel) has been reported from few tens of kilometres (River Ebro, Petts and Gurnell, 2005) to hundreds of km (River Mississippi, Williams and Wolman, 1984).

Table 4
*Correlation matrix between Geomorphic Status –GS and degree of regulation (as per Batalla et al., 2004), where IR_r means the impoundment ratio in relation to the single upstream reservoir and IR_t means the impoundment ratio related to all upstream reservoirs (*statistically significant at 0.05 confidence level).*

	GS	IR_r	IR_t
GS	1	-0.35*	0.02
IR_r	-0.35*	1	0.24
IR_t	0.02	0.24	1

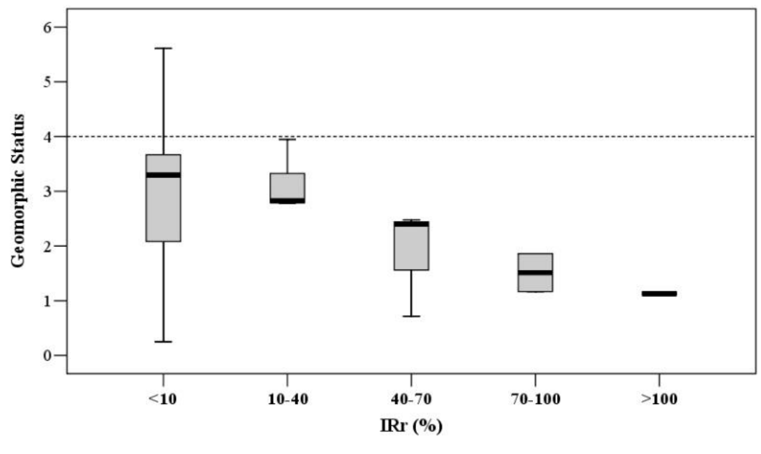

Figure 8. *Box plot of the Geomorphic Status — GS in relation to different degrees of impoundment. Horizontal dotted line indicates no change, >4 implies an improvement and <4 implies a deterioration, between reference and the current periods. The medians (central bar), 25th–75th quantiles (box) and non-outlier range (whiskers) are shown in the plot (outliers not shown).*

It is also worth pointing out the fact that some of the not regulated sites with a very low GS (i.e. ANO2, ANO3, CAB2, CAB3) can be related to the reduction of the floods due to the huge reforestation of the basin. On the other hand, MAG1 also shows a very low GS due to land use changes but, in this case, to the fact that riparian forests have been substituted by agriculture, thus limiting channel mobility, a phenomenon which is typically enhanced by engineering works that are usually associated (e.g. embankments and rip-raps).

Finally, the multiple regression analysis between geomorphic indices (i.e. SU, SA, BS, CF and GS) and impact variables (i.e. IR_r, number of tributaries, and distance to the dam) yielded only a few statistically significant relations (Table 5). Overall, regulation was negatively correlated with the abundance of active areas and GS. Furthermore, the number of tributaries and the distance from dams were significantly correlated only with change in flow capacity, with β coefficients of −0.47 and +0.51, respectively. Distance and number of tributaries could not reverse the local impact of the dam, since it is known that, for many rivers, headwaters provide typically more than 3/4 of the sediment load (e.g. Petts and Gurnell, 2005) which, in this situation, is captured by dams.

Table 5

Multiple regression between geomorphic variables and impoundment ratio (IR_r), number of tributaries and distance to the dam (+statistically significant at 0.1 confidence level).

	IR_r	Number of tributaries	Distance (km)
SU[1]	-0.25	-0.18	0.26
SA[2]	-0.34^{+}	0.01	-0.03
BS[3]	-0.32	0.01	-0.05
CF[4]	-0.12	-0.47^{+}	0.51^{+}
GS[5]	-0.35^{+}	-0.16	0.17

[1] *Changes in sedimentary unities*
[2] *Changes in sediment availability*
[3] *Changes in bar stability*
[4] *Changes in channel flow capacity*
[5] *Index of Geomorphic Status-GS*

At-a-site complexity was related to upstream basin characteristics. Headwater sites (Cluster #1) presented a complex channel structure in the reference image (Fig. 9), but most (90%) were subsequently affected by regulation. Sites in this cluster showed the largest reduction in the number of total and active bars, and a substantial increase in the vegetated ones. The lowermost reaches (Cluster #2) showed little changes in morphological structures between periods of analysis (here 100% of the sites are regulated). Results suggest that the rivers were already stabilized (i.e. most of the bars were vegetated in the reference image) before dam construction.

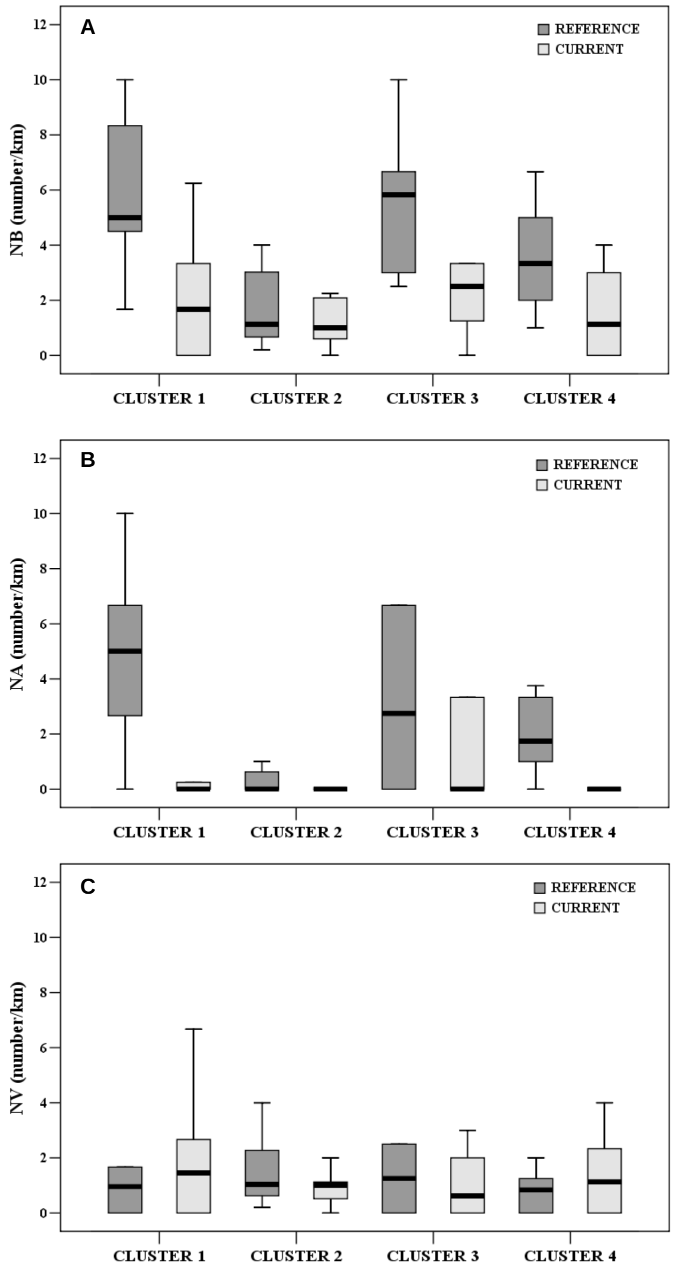

Figure 9. *Box plots of the geomorphic parameters for reference and current stream conditions in each cluster: (A) number of total bars (NB) divided by channel length. (B) number of active bars (NA) divided by channel length. (C) number of vegetated (NV) bars divided by channel length. The medians (central bar), 25th–75th quantiles (box) and non-outlier range (whiskers) are shown in the plot (outliers not shown).*

This finding is found to be consistent with a study in the lower Rhône River (Provansal et al., 2014) where the changes in the sediment balance and its consequences on channel morphology were already important following reforestation and engineering works at the beginning of the 20th century; consequently, dams built up over the last 50 years would have been of lesser impact. The *Mediterranean sites* (Cluster #3) showed the highest variability regarding channel features, mainly in relation to active bars. It must be noted that more than half of the sites of this group were excluded from the analysis because they did not show any geomorphological structure in the reference aerial photographs. The main reason for this relies on the fact that in the 1970s (reference image) the margins and river banks were already occupied by agriculture. Sites in Cluster #4 (mid-size basins) showed a notable geomorphic complexity in the reference image, but less active bars and more vegetation in the present situation.

Overall, rivers in Cluster #1 showed the greater decline in the sedimentary activity (Fig. 9). In general terms, the degree of activity of a given channel depends directly on the flow competence and the sediment supply. Cluster #1 are headwater sites that generally have a great potential for bedload transport, on which river forms are built up, and exhibit frequent competent episodes (flows). Therefore, when such a dynamic system is altered by a dam, the system cuts-off and channel forms adapt to it, typically losing dynamism.

4.4. Hydrological and geomorphological responses

Hydrological alteration implies a change in the flow energy budget below the dam, and this generally brings a geomorphic adjustment of the river downstream. In our case, a correlation analysis between hydrological (Q_a, NLF, NHF, NR, Q_2,Q_{10} and Q_{25}; Table 1) and geomorphological (i.e. SU, SA, BS, CF and GS; Table 1) variables for the 19 river reaches (Fig. 3) was carried out (Table 6). Results showed that the reduction in reach complexity is positively correlated with a decrease in the magnitude and frequency of high flows (Q_2,Q_{10} and Q_{25}). The decline in active bars and the increment in vegetated bars were particularly related to Q_2, and consequently, the decrease in GS followed mostly with the decline of relatively frequent floods. The discharge that transports most of the sediment over the long term is commonly termed ‘effective’ discharge, whereas the discharge performing most of the geomorphic work in the channel is termed dominant, both generally related to bankfull level, whose recurrence intervals have been accepted between 1 and 2 years for many rivers (Leopold et al, 1964). Other studies (e.g. Surian, 1999) suggest that channel morphology has adjusted to the post-dam relatively frequent floods (i.e. up to around bankfull, Q_2), rather than to the large events. It is worth noting that changes in hydrology and the reduction in the active width were not significantly correlated in our work (Table 6), suggesting that other factors may influence such reduction as vegetation encroachment and human activities (e.g. agricultural intrusion). Frequently, regulation increases summer flows for irrigation purposes (Batalla et al., 2004), and may cause the growth and stabilization of vegetation in the channel (Magdaleno and Fernández, 2011). Although such vegetation may decrease channel mobility, riparian areas provide important other functions to the fluvial system such as nutrient cycling, flood attenuation, carbon dioxide sequestration, sediment deposition and wildlife habitat (Sharitz and Mitsch, 1993). Moreover, in the absence of recurrent floods, fluvial territory is progressively invaded by human activities yielding a reduction in the active area. The riparian vegetation communities are very sensitive to changes in flood frequency, and species not adapted to inundation or saturation are restricted to the higher riparian elevations; therefore, the alteration of flow in regulated rivers has also effects on the riparian communities, and may result in changes in the community assemblage by reducing the biodiversity of wetland-adapted plants and animals (Alldredge and Moore, 2014).

Table 6.
*Correlation matrix between geomorphic and hydrologic variables (§ indicates the ratio between post and pre-dam values and * indicates significant correlation at 0.05 confidence level).*

	§DMF[a]	§NLF[b]	§NHF[c]	§NR[d]	§Q_2[e]	§Q_{10}[e]	§Q_{25}[f]
SU[1]	0.15	0.00	-0.31	0.08	0.66*	0.65*	0.65*
SA[2]	0.19	-0.11	0.02	0.04	0.51*	0.41	0.40
BS[3]	0.18	-0.10	0.03	0.06	0.51*	0.40	0.39
CFC[4]	-0.02	0.01	-0.15	0.10	-0.13	-0.09	-0.07
GS[5]	0.18	-0.08	-0.12	0.09	0.57*	0.49	0.49

[1] *Changes in sedimentary unities*
[2] *Changes in sediment availability*
[3] *Changes in bar stability*
[4] *Changes in channel flow capacity*
[5] *Index of Geomorphic Status*
[a] *1-day maximum flow (as per Richter et al., 1996; see table 1 for definition)*
[b] *Number of low flow pulses*
[c] *Number of high flow pulses*
[d] *Number of reversals*
[e] *Flood with 2, 10 and 25 years of return period, respectively*

Finally, in addition to the historical analysis, an examination of the current status of the study sites was also carried out based on field data and hydrological series available at the selected sites (Table 7). The aim of this analysis was to determine differences between regulated and not regulated rivers regarding their present geomorphological activity. Overall sampled sites in not regulated rivers showed a higher degree of fluvial activity than their regulated counterparts, except for two cases; these two sites (GUAN and JUC1, Table 7) belong to groups #3 and #4 (i.e. areas showing marked Mediterranean trends). Not-regulated sites are less armoured and have high instantaneous torrentiality (mean of Q_{ci}/Q_n = 55), altogether suggesting that channels are still active (Table 7). In contrast, sites in rivers experiencing regulation show a lower degree of fluvial activity; except for three sites (CAR1, GAL2 and ZAD, Table 7), the rest belong mostly to groups #1 and #2 (i.e. headwater basins where most of dams in the basins are located, and lowland basins where fluvial landscapes use to be naturally gentle and geomorphic processes of low intensity) and show armoured riverbeds. At these sites instantaneous torrentiality is much lower than in the Mediterranean sites (mean of Q_{ci}/Q_n = 13.6), altogether suggesting less intense morphosedimentary processes, and reflecting the influence of upstream regulation in their water and sediment budgets, thus in channel form and dynamics. Rivers downstream from a dam response mainly to the lack of sediment (i.e. sediment eroded from the bed is not replace with solid load coming from upstream); but also to the reduction in the competence of flood discharge that, in turn, favours the encroachment of vegetation in formerly active areas, that, subsequently, reduces the local in-channel availability of sediment. This feedback phenomena is well-know and our results point to the same direction, corroborating previous observations reported elsewhere (e.g. Williams and Wolman, 1984; Surian, 1999, Vericat et al., 2006). Moreover, our analysis put these findings into a broader perspective by examining channel activity in regulated rivers along a latitudinal gradient that covers different climatic subregions (here represented by four statistically significant clusters). The geographical amplitude of this work also points out the internal differences in each of the regions, a fact that demonstrates the complexity of the adjustments that take place in a river affected by upstream reservoirs, precluding the use of simple generalizations at assessing implications for river conservation and implementing classic restoration measures.

Table 7
Hydrological and geomorphological indicators derived from field data selected sites in not regulated and regulated rivers. Mean values are discussed in text (see details in sections 4.2 and 4.3).

		Location[a]		**Torrentiality**[b]		**Dynamism**[c]	
	Site	**Basin**	**#Cluster**	**Instant.**[d]	**Daily**[e]	**Shear stress**[f]	**Armouring**[g]
Not regulated	**RS**	Ebro	1	nd[h]	nd	4.4	nd
	BOR	Guadalquivir	1	nd	nd	56.8	nd
	CAC	Guadalquivir	3	27.2	9.8	4.6	1.39
	GUAL	Guadalquivir	3	nd	nd	18.2	3.08
	GUAN	Guadalquivir	3	17.4	12.5	12.1	3.28
	HER	Guadalquivir	3	nd	nd	151.9	nd
	PIC	Guadalquivir	3	nd	nd	20.7	1.63
	ALG	Ebro	4	87.8	34.8	34.5	1.20
	MAR	Ebro	4	27.3	9.2	61.7	1.33
	MAT	Ebro	4	146.3	32.2	10.5	1.35
	ANO3	Llobregat	4	64.9	16.8	34.9	nd
	CAB1	Júcar	4	nd	nd	34.4	6.01
	JUC1	Júcar	4	14.0	6.9	91.6	nd
	Mean			**55.0**	**17.5**	**41.3**	**2.4**
Regulated	**ARG**	Ebro	1	15.4	12.7	1.3	8.54
	CIN1	Ebro	1	9.4	5.8	29.0	1.55
	CIN2	Ebro	1	12.0	7.4	nd	1.09
	ESE	Ebro	1	10.6	5.7	7.8	5.85
	CAR1	Llobregat	1	24.7	9.7	18.9	1.18
	CAR2	Llobregat	1	10.1	9.5	16.2	nd
	JUC4	Júcar	2	2.8	2.3	31.2	nd
	EBR6	Ebro	2	nd	nd	nd	1.54
	GAL2	Ebro	4	20.7	12.8	nd	1.63
	HUE	Ebro	4	9.4	5.6	8.2	nd
	ZAD	Ebro	4	20.4	15.7	5.9	6.59
	Mean			**13.6**	**8.7**	**14.8**	**3.6**

[a] See section 3.2.1. in the text for details
[b] Ratio between Maximum Discharge and Mean Discharge; used here as a proxy of Mediterraneity
[c] Force and resistance factors indicating degree of geomorphic activity in the channel
[d] Ratio between the Mean of the Annual Maximum Instantaneous Discharge -Q_{ci} and the Mean Discharge
[e] Ratio between the Mean of the Annual Maximum Daily Discharges -Q_c and the Mean Discharge
[f] Shear stress at bankfull (N/m^2)
[g] Armouring ratio (Ratio between Median Surface Diameter and Median Subsurface Diameter; see section 3.1.6. for details)
[h] no data available; due to technical difficulties the site could not be (fully) surveyed.

5. FINAL REMARKS

This work examines the effects of flow regulation on the geomorphologic activity in selected river sites of four large basins in the Iberian Peninsula. A Geomorphic Status (GS) index that allows assessing the potential geomorphic activity (i.e. dynamism) at a given river reach and its change through time has been used to assess channel response to regulation; in addition, ad-hoc field data is analysed to describe the current activity of the study reaches. Hydrological trends geomorphic activity is also examined in not regulated rivers that allow illustrating changes beyond regulation. Conclusions from the work can be drawn as follows:

1) Regulation of these Iberian rivers produces a decrease in the annual stream flow and in the magnitude and frequency of floods, together with an increase in the frequency of low discharges and in the number of reversals. These hydrological changes result mainly in the loss of active bars as they are encroached by vegetation, to the point that only sites with little or no regulation display active bars.
2) Accordingly, the geomorphic activity (as represented by GS) declines with regulation (best represented by the local impoundment ratio, IR_r). In contrast to hydrology, distance and number of tributaries does not reverse the geomorphic impact of the dam. Field data corroborates the reduction of the morphosedimentary activity in river reaches located downstream from dams, with less energy expenditure and higher riverbed armouring.
3) Headwaters sites are especially affected by regulation, reducing their activity and forcing them to experience low-energetic processes such as those situations typical from lowland rivers with highly stable beds.
4) Finally, the reduction in reach complexity relates positively with the decrease in the magnitude and frequency of high flows; particularly the decline in active bars and the increment in vegetated bars are well correlated with Q_2 (assumed here as a proxy of the bankfull discharge).

Overall, our results indicate that dams have progressively altered the geomorphic status of Iberian rivers and raises concerns about the possibilities to attain a good status according to the various EU directives related to rivers and river habitats. The novel Geomorphic Status index complements the available Hydrological Alteration indices and may aid further developments of the current tools to characterise the hydromorphology of altered systems, as it is required by River Basin Management Plans. Information shall inform as well on a variety of restoration actions, such as the design and implementation of flushing flows (i.e. artificial flow releases from dams aiming at enhancing morphosedimentary processes in the channel), together with the simultaneous injection of sediments, to recreate channel forms and the associate habitat for targeted species.

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Supplementary material (Site location in each basin)

Code	Location[a]	Cluster#	A[1]	Pm[2]	IR_r[3]	GS[4]	DMF_{pre}[5]	DMF_{post}[5]
Ebro								
ZAD	517751,4742340[b]	4	888	956	0.39	nd[d]	129	107
OCA	466404,4733188[b]	4	1083	647	-	nd	28	-
NAJ	523728,4703490[b]	1	1072	828	0.46	2.4	140	70
MAT	262590,4564216[a]	4	1036	548	-	3.6	33	-
HUE	673706,4609072[b]	2	1038	444	0.09	nd	nd	13
MAR	693322,4536028[b]	4	590	482	-	3.4	6	-
RS	370236,4658097[a]	1	115	958	-	3.3	nd	nd
GAL1	714824,4705759b	1	802	1425	0.001	0.7	14	17
GAL2	681867,4622636b	2	3784	787	0.01	3.1	nd	209
CIN1	271028,4667069a	1	2154	1198	0.28	2.8	402	153
CIN2	264643,4642481[a]	1	4574	1042	0.33	2.8	342	297
EBR1	405418,4761647[b]	1	11	905	-	nd	8	-
EBR2	503744,4726338[b]	2	5366	777	0.01	3.6	594	533
EBR3	513217,4715954[b]	2	7303	807	0.01	nd	nd	673
EBR4	565450,4696350[b]	2	11935	774	0.0003	2.9	nd	716
EBR5	619241,4653999[b]	2	26236	820	0.0001	4	nd	1657
EBR6	693338,4603748[b]	2	46343	690	0.0001	3.3	nd	nd
EBR7	405301,4761851[b]	2	82934	656	0.001	3.7	nd	1678
EBR8	294655,4513798[a]	2	85065	654	0.001	1.9	2849	1755
EBR9	306867,4509550[a]	2	85380	653	0.001	4	nd	nd
ALG	265648,4554169[a]	2	324	526	-	4.3	14	-
SEG	292281,4601094[a]	2	12255	707	0.004	3.2	nd	300
ESE	776303,4678225[b]	1	894	1199	0.005	3.4	130	108
ARG	598806,4738107[b]	1	1802	1263	0.016	2.3	447	457
Llobregat								
LLO1	416185,4679296[a]	1	28	924	-	nd	7	-
LLO2	407124,4659479[a]	1	534	888	0.631	0.7	47	33
LLO3	405980,4617599[a]	4	1883	765	0.439	2.5	84	66
LLO4	404144,4612208[a]	4	3330	739	0.238	3.9	150	128
LLO5	406688,4601860[a]	4	3450	734	0.208	3.2	nd	nd
LLO6	409900,4595207[a]	4	3578	731	0.227	1.0	201	125
LLO7	420340,4578442[a]	4	4850	699	0.243	2.8	210	143
CAR1	381490,4651384[a]	1	253	913	0.913	1.2	27	8
CAR2	385178,4644519[a]	1	314	875	0.207	3.5	23	22
CAR3	397244,4629111[a]	4	1017	759	0.202	nd	nd	22
CAR4	404123,4615251[a]	4	1410	708	0.130	nd	40	38
ANO1	378867,4606051[a]	4	215	536	-	nd	4	-
ANO2	388318,4602195[a]	4	375	555	-	1.4	4	-
ANO3	401024,4586961[a]	4	732	584	-	2.3	17	-
Júcar								
MAG1	667953,4362485[b]	4	777	472	-	0.5	6	-
MAG2	710987,4349519[b]	2	1532	480	0.565	nd	5	1
CAB1	627162,4439393[b]	4	351	740	-	nd	nd	nd
CAB2	612356,4422534[b]	4	818	689	-	0.6	33	-
CAB3	608420,4415400[b]	4	1029	665	-	0.3	30	-
CAB4	628444,4376765[b]	4	3319	598	1.738	nd	116	30
CAB5	641541,4356608[b]	2	3795	575	1.520	3.8	nd	nd
JUC1	598572,4453965[b]	4	255	838	-	nd	15	-
JUC2	573061,4436071[b]	4	1003	813	0.034	nd	114	74
JUC3	561838,4414529[b]	4	1812	728	0.034	3.6	nd	67
JUC4	601886,4335908[b]	2	3698	617	1.755	nd	167	35

JUC5	665932,4340489[b]	2	10744	502	0.006	nd	35	35
JUC6	707816,4328377[b]	2	17007	515	0.248	nd	174	36
JUC7	720547,4336875[b]	2	19638	518	0.245	nd	nd	nd
JUC8	729567,4343224[b]	2	21409	516	0.276	nd	221	66
Guadalquivir								
BEM	279558,4224980[b]	3	557	548	-	3.8	nd	nd
CAC	423215,4086558[b]	3	24	612	-	nd	nd	-
GEN1	396131,4116705[b]	3	4074	559	-	nd	68	-
GEN2	314861,4161651[b]	3	7978	558	0.087	3.4	nd	55
GUA1	497243,4214531[b]	1	750	938	2.127	nd	nd	27
GUA2	455224,4199419[b]	3	9380	525	0.030	2.7	210	83
GUA3	395554,4208071[b]	2	20665	550	0.006	nd	617	238
GUA4	335035,4190261[b]	2	27794	568	0.003	1.4	nd	361
GUA5	281638,4172673[b]	2	41749	574	0.001	4.0	984	801
GUAL	375633,4167015[b]	3	73	572	-	nd	nd	-
GUAN	432004,4199528[b]	3	1042	599	-	5.6	39	-
GUAZ	340156,4187958[b]	3	2406	604	1.090	1.1	73	28
MAG	456440,4242566[b]	3	207	551	-	nd	nd	-
YEG	384792,4246926[b]	3	129	648	-	nd	17	-
BOR	512435,4207324[b]	1	133	1116	-	nd	nd	-
COR	273116,4154005[b]	3	1355	585	0.443	nd	16	20
GUAA	267899,4123848[b]	3	268	603	-	nd	29	-
GUAM	480682,4195240[b]	3	7129	468	0.944	1.9	42	13
GUAR	742849,4130702[c]	3	879	658	-	nd	62	-
HER	235193,4156868[b]	3	42	645	-	nd	nd	-
PIC	315118,4181014[b]	3	45	592	-	nd	nd	-

[1] *Basin area (km^2)*
[2] *Mean annual precipitation (mm)*
[3] *Local impoundment ratio*
[4] *Geomorphic Status index -GS*
[5] *Pre and post-dam 1-day maximum flow (as per Richter et al., 1996; see table 1 for definition)*
[a] *Spindle 31*
[b] *Spindle 30*
[c] *Spindle 29*
[d] *No data available*

Chapter 4

Sediment transport in two Mediterranean regulated rivers

The objective of this chapter is to assess water and sediment fluxes upstream and downstream from dams in two Mediterranean rivers with contrasting mediterraneity. The chapter contains the following accepted and already published paper:

Lobera G, Batalla RJ, Vericat D, López-Tarazón JA, Tena A. 2015. Sediment transport in two mediterranean regulated rivers. Science of the Total Environment. Science of the Total Environment; 540: 101-113. *Impact factor (2015):* 3.976; *Area:* Environmental Sciences; *Quartile:* 1st.

Summary: runoff and suspended sediment loads are analysed in two climatically-contrasting Mediterranean regulated rivers (i.e. the Ésera and Siurana) during two consecutive years upstream and downstream from dams. Results indicate how dams can modify the hydrological character of Mediterranean rivers and how this controls sediment transport dynamics downstream. Relatively humid regimes may become quasi-permanent low flow regimes, while a flashy (rapid) and highly dynamic ones may become more constant.

Key Words: Mediterranean Rivers, Siurana, Ésera, suspended sediment transport, sediment load, water yield, floods, flashy, regimes, dams,

ABSTRACT

Mediterranean climate is characterized by highly irregular rainfall patterns with marked differences between wet and dry seasons which lead to highly variable hydrological fluvial regimes. As a result, and in order to ensure water availability and reduce its temporal variability, a high number of large dams were built during the 20th century (more than 3,500 located in Mediterranean rivers). Dams modify the flow regime but also interrupt the continuity of sediment transfer along the river network, thereby changing its functioning as an ecosystem. Within this context, the present paper aims to assess the suspended sediment loads and dynamics of two climatically contrasting Mediterranean regulated rivers (i.e. the Ésera and Siurana) during a 2-yr period. Key findings indicate that floods were responsible for 92% of the total suspended sediment load in the River Siurana, while this percentage falls to 70% for the Ésera, indicating the importance of baseflows on sediment transport in this river. This fact is related to the high sediment availability, with the Ésera acting as a non-supply-limited catchment due to the high productivity of the sources (i.e. badlands). In contrast, the Siurana can be considered a supply-limited system due to its low geomorphic activity and reduced sediment availability, with suspended sediment concentration remaining low even for high magnitude flood events. Reservoirs in both rivers reduce sediment load up to 90%, although total runoff is only reduced in the case of the River Ésera. A remarkable fact is the change of the hydrological character of the River Ésera downstream for the dam, shifting from a humid mountainous river regime to a quasi-invariable pattern, whereas the Siurana experiences the opposite effect, changing from a flashy Mediterranean river to a more constant flow regime below the dam.

1. INTRODUCTION

Mediterranean climate is characterized by a highly variable and irregular rainfall regime with marked differences between wet and dry seasons. Consequently, Mediterranean rivers are physically, chemically, and biologically shaped by sequential seasonal events of flooding and drying over a yearly cycle (Gasith and Resh, 1999). Moreover, Mediterranean regions are often rugged, marked by a notable altitudinal gradient between the headwaters and the outlet; hence large climatic heterogeneity can be found along relatively short horizontal distances, with mean annual precipitation usually ranging from 275 to > 900 mm (Aschmann, 1973). Mediterranean streams, which are located in high elevated areas and experience annual rainfall exceeding 1000 mm, are characterized by low temperatures in winter with the chance of snow accumulation. This creates a typically bimodal pattern in the flow regime, with the highest discharge following the onset of rain and following snowmelt in spring (e.g. Sabater et al., 1992), but maintaining a permanent flow throughout the year. In contrast, rivers located in semi-arid areas, with mean annual precipitation ranging from 200 to 500 mm, show a less permanent flow regime. This is usually classified as i) ephemeral, in which the stream bed dries up during the summer or even for longer periods and ii) intermittent, in which despite the stream bed drying up, some pools remain wet but isolated during the driest season (summer) (e.g. Gasith and Resh, 1999; Bonada et al., 2007a).

Water resources in Mediterranean areas are subjected to rising pressures and have become a key issue for governments as water becomes scarce due to the imbalance existing between the available resources and the increasing water demands (e.g. Milly et al., 2005). In this context, a huge number of large dams have been built during the 20th century to ensure water availability and reduce its temporal variability, with more than 3,500 of them located in Mediterranean rivers (Cuttelod et al., 2008). Dams modify the flow regime and interrupt the continuity of sediment transfer along the river system, thereby changing its character and functioning (e.g. Kondolf, 1997; Hauer and Lorang, 2004; Grantham et al., 2013). Hydrological alterations below dams include changes in flood frequency and magnitude, and changes in seasonal patterns and timing of releases (e.g. Ward and Stanford, 1979; Petts, 1984; Ligon et al., 1995; Ward and Stanford, 1995; Batalla et al., 2004). Furthermore, bedload and most of the suspended sediment is trapped by reservoirs, thus reducing sediment supply to downstream reaches and the coastline (e.g. Vericat and Batalla, 2006; Frihy et al., 2008). In addition, water released from dams with the potential to erode and move coarse sediment, but with little or no sediment supply from upstream, becomes *hungry water* (Kondolf, 1997). The main consequences of such hungry water include: i) river channel degradation, especially through bed incision (Simon and Rinaldi, 2006), coarsening (i.e. armouring) of the surface layer (Vericat and Batalla, 2006) and channel narrowing (Liébault and Piégay, 2001); ii) ecological degradation, damaging the availability and quality of the habitat for both the aquatic and riparian biota (Gendaszek et al., 2012); and iii) reduction of the sediment supply to the development of the river delta and hence accelerated coastal erosion (Kondolf, 1997). On the other hand, when flow competence is reduced, if there is any sediment supply coming from tributaries or any other source (e.g. bank collapse), and the altered flow is not capable to transport sediment downstream, channel aggradation may occur.

Different management strategies have been developed and are being used worldwide to mitigate the impacts of dams on rivers. Flushing flows have been used to remove fine sediment accumulations and scour the channel bed (e.g. Milhous, 1982; Reiser et al, 1989), and to maintain the habitat for the freshwater organisms and the riparian vegetation (Kondolf and Wilcock, 1996). Flushing flows have been implemented, for instance, in the lower Ebro (Batalla and Vericat, 2009; Tena et al., 2012) to mobilize the coarse particles of the channel bed and hence detach the macrophytes rooted to them (the exponential growth of macrophytes is a typical phenomenon of regulated rivers experiencing low frequency of competent floods). In addition to flushing flows, other measures aimed to solve reservoir siltation and hence progressively reduce their water storage capacity have been developed: i) to reduce the sediment yield of the basin, hence decreasing the sediment input to the reservoir; ii) to pass sediment through or around the reservoir downstream; and iii) to dredge the accumulated sediment. However, the high costs of these operations often limit their application (Fan and Springer, 1993).

As a result of the climatic variability of Mediterranean river basins, it is still difficult to describe general patterns which explain and predict the relations between runoff, erosion and sediment transport (de Vente et al., 2005; López-Tarazón et al., 2010); and this is even more complicated in rivers affected by regulation where, in addition, time-series on sediment transport are typically scarce (Batalla and Vericat, 2011). Within this context, this paper aims to study the suspended sediment loads and dynamics of two climatically contrasted impounded rivers in the Western Mediterranean region (i.e. the rivers Ésera and Siurana, both in the Ebro basin), to specifically assess the effects of damming on water and sediment fluxes. The work is done over a 2-year period during which continuous suspended sediment and flow data were obtained to examine the role of large reservoirs on cutting sediment transfer in these two rivers. Suspended sediment transport is analysed in both rivers following a control-impact concept, in reaches located immediately upstream and downstream from large reservoirs, to compare its dynamics and the effects of river regulation on the solid load at different timescales. Data of such quality in this type of rivers is seldom if ever available, so results allow characterising in detail the role of large dams on water and sediment dynamics. The analysis of catchment-scale relations that would eventually explain the specific process controlling sediment yield in these rivers is not in the scope of the present paper.

2. STUDY AREA

This research is conducted in two catchments located in the NE of the Iberian Peninsula: the rivers Ésera and Siurana (Fig. 1). In the following section we present the general characteristics of the basins together with a description of the sites where flow and sediment transport have been monitored.

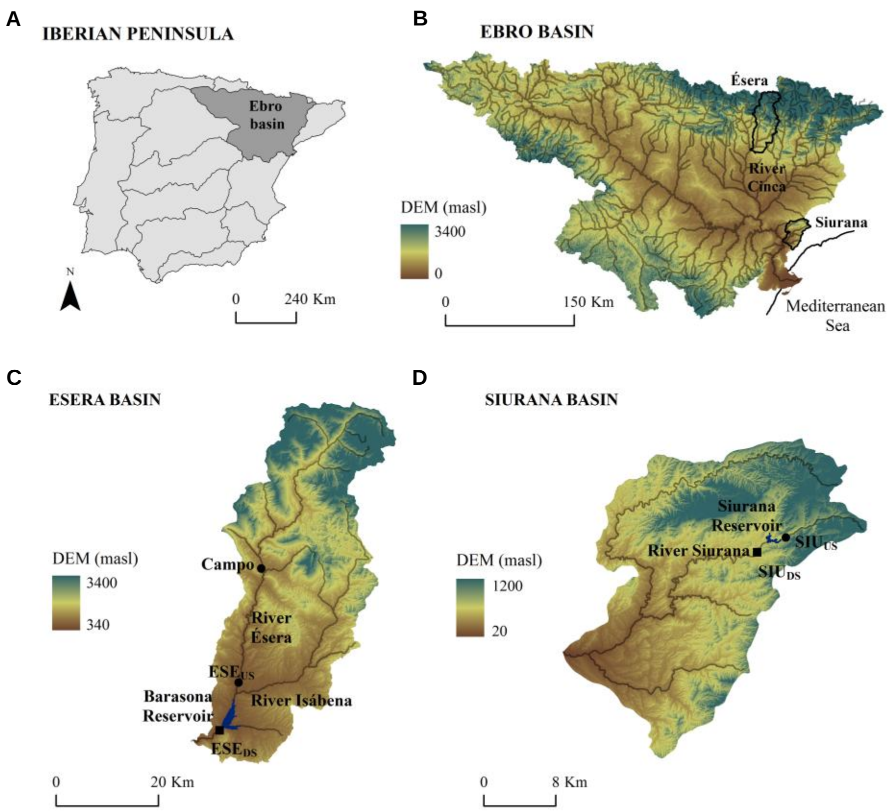

Figure 1. *(A) Location of the Ebro catchment in the Iberian Peninsula. (B) Location of the Ésera and Siurana basins in the Ebro catchment. (C) Location of the study sites (ESE_{US} and ESE_{DS}) upstream and downstream of the Barasona Reservoir in the Ésera river basin. (D) Location of the study sites (SIU_{US} and SIU_{DS}) upstream and downstream of the Siurana Reservoir in the Siurana river basin.*

2.1. The Ésera basin

The Ésera is a mountainous catchment located in the South Central Pyrenees. It drains an area of 1,484 km^2 at the inlet of the Barasona Reservoir, and it is the second largest tributary of the River Cinca, which in turn is the second main tributary of the River Ebro (Fig. 1). Around 84% of the basin area is occupied by forests, mainly coniferous forest (20%) and shrub and/or herbaceous vegetation (33%) (according to Corine Land Cover 2006 database, EEA, 2006). Elevation ranges from 3,400 m a.s.l. in the headwaters to 340 m a.s.l. at the outlet. Climatically, the basin belongs to the Continental

Mediterranean domain, with mean annual precipitation ranging from 420 mm in the lowland to 2,500 mm at the summit (the average value for the whole catchment is 1,070 mm). The hydrology of the basin is characterized by a nivo-pluvial regime. Floods normally take place in spring, mainly as a result of snowmelt associated with frontal precipitation and, also in late summer and autumn, as a consequence of localized thunderstorms associated with convective rainfall.

The Barasona dam (Fig. 1c) was closed in 1932 with the main purpose of irrigation and power supply. The initial water capacity was 71 hm^3, but it was enlarged in 1972 providing a final storage capacity of 92 hm^3, impounding up to 15% of the mean annual runoff. The dam is mainly operated to supply water to the Canal of Aragón and Catalunya, which irrigates more than 100,000 ha in the lowland. Since its construction, the reservoir experiences acute siltation problems at a rate of up to 0.3 and 0.5 hm^3 of deposited sediment annually (Francke, 2009). Engineering works were carried out between 1995 and 1997 to release sediment through the dam bottom outlets. These operations finally resulted in more than 9 hm^3 of sediment sluiced downstream (Palau, 1998; Avendaño et al., 2000). However, it has been estimated that the current reservoir capacity already equals that prior to sluicing operations: 76 hm^3 (Mamede, 2008).

The mean annual discharge of the Ésera in Graus, upstream from the confluence with its main tributary (the Isábena) (Fig. 1c) is 17.6 m^3 s^{-1}, while the maximum peak flow ever measured (August 1963) was 995 m^3 s^{-1} (a discharge with a return period of more than 100 years, calculated from the series of annual maximum instantaneous discharge by the Gumbel method for the period 1949-2007). Mean annual water yield is 555 hm^3 (620 mm y^{-1}). It is worth noting the presence of daily flow fluctuations (i.e. hydropeaking) generated on a weir that uses water for hydropower energy production, located in Campo around 30 km upstream from Graus (Fig. 1c). Discharge fluctuates according to energy demand, typically ranging from 2 to 20 m^3 s^{-1}. The main tributary of the Ésera is the Isábena (Fig. 1c), which drains to the Ésera a few hundred meters downstream from the monitoring site. Mean water yield of the Isábena is 170 hm^3 (382 mm y^{-1}). Sediment transport in the Isábena has been studied since 2002. Mean flood suspended sediment concentration was 7.7 g l^{-1} for the period 2005-2008 (López-Tarazón et al., 2009), with maximum instantaneous concentrations reaching values up to 350 g l^{-1} (López-Tarazón et al., 2011). Concentrations up to 1 g l^{-1} are usually reported during low flows. Cycles of sediment production, transfer, in-channel sediment accumulation and export have been described by López-Tarazón et al. (2012). These cycles are controlled by local sources of sediment that occupy a small area (1%) of the catchment, but produces almost all of the sediment. These areas are characterized by the presence of badlands with highly erodible Eocene marls (López-Tarazón et al., 2009, Vericat et al., 2014).

Flow downstream from the dam is very low most of the time. Flow magnitude is determined by the ecological flow requirements, with the exception of exceptional water releases for dam maintenance and flood management when necessary. For reference, the maximum discharge ever recorded was 505 $m^3 s^{-1}$ in 1997, corresponding to a recurrence interval of approximately 100 years, calculated by the Gumbel method with the series of annual maximum daily discharge for the period 1992-2012. Mean annual discharge during the study period was 2 $m^3 s^{-1}$ although the flow was stable at around 0.3 $m^3 s^{-1}$ 90% of the time, as it will be specifically reported in Section 4. Mean annual water output from the dam is 69 hm^3, a value that equates to 9.5% of the input at the inlet of the reservoir.

2.2. The Siurana basin

The River Siurana is the main tributary of the Lower Ebro River downstream the Mequinenza-Ribarroja-Flix dams complex (NE of the Iberian Peninsula; Fig. 1). The River Siurana drains a total area of 610 km^2, 49% of which is occupied by forests and natural vegetation and the rest by agriculture (according to Corine Land Cover 2006 database, EEA, 2006). However, the predominant land use of the reservoir draining the catchment is forest and natural vegetation, representing 81% of the total area (i.e. 47% coniferous forest and 21% shrubs and/or herbaceous vegetation). Elevation ranges from more than 1200 m a.s.l. at the headwaters to 20 m a.s.l. at the basin outlet in the Ebro. The climate is typically Mediterranean, with mean annual rainfall of 500 mm (ranging from 400 to 700 mm), 80% of which is concentrated between October and April, followed by dry summers (Candela et al., 2012). The rainfall regime is characterized by its high torrentiality, producing floods with a steep raising limb as a consequence of intense thunderstorms, especially during spring and autumn. Owing to this rainfall pattern, the River Siurana is representative of a rainfall-based flow regime with marked seasonality.

The Siurana Reservoir is located in the upper part of the basin, impounding 12% of the total basin area (Fig. 1d). The dam was built in 1972 with the main purpose of irrigation and water supply. The storage capacity is 12 hm^3, impounding 2.7 times the mean annual runoff of the basin (i.e. 4.4 hm^3). Mean annual discharge is around 0.14 $m^3 s^{-1}$ (60 mm y^{-1}), while the maximum instantaneous discharge recorded between 2011 and 2013 was 33 $m^3 s^{-1}$ (recorded in March 2013). The minimum observed flow was 0.02 $m^3 s^{-1}$, but the river never dried up. The mean flow registered downstream from the dam was 0.16 $m^3 s^{-1}$ (2011-2013), while the maximum peak discharge was 5.3 $m^3 s^{-1}$.

3. METHODS

The monitoring period extended from October 2011 to October 2013 at all study sites. The upstream monitoring section in the River Ésera (ESE_{US}; Fig. 1c) is located 3 km from the inlet of the Barasona Reservoir. The drainage area at this section is 894 km^2, 67% of the area contributing to the Barasona. Discharge is recorded at the gauging station EA013 located in the village of Graus. The downstream monitoring section (ESE_{DS}; Fig. 1c) is located around 500 m below the dam.

The upstream monitoring section in the River Siurana (SIU_{US}, Figure 1d) is 500 m from the inlet of the Siurana Reservoir. The downstream monitoring section (SIU_{DS}; Fig. 1d) is located 500 m below the dam. It is worth mentioning the existence of a small (3 km^2) ephemeral tributary (dry most of the time), which drains into the main channel between the dam and SIU_{DS}.

3.1. Flow discharge

Discharge was measured by means of different methods and techniques selected according to the characteristics of the monitoring sites. At ESE_{US}, flow data was provided by the Ebro Water Authorities (CHE), which measures water stage (*h*) continuously at the EA013. Data is recorded every 15-min and then transformed into discharge (*Q*) by means of the corresponding *h*/*Q* rating curve. At all other sites (ESE_{DS}, SIU_{US} and SIU_{DS}) water stage was measured at 15-min intervals using capacitive water stage sensors (TruTrack® WT-HR). Stage (*h*) was later converted into *Q* by applying on-site *h*/*Q* rating curves obtained from direct measurements, hydraulic modelling and routed data from nearby gauging stations. At ESE_{DS} the rating curve was obtained from direct discharge gauges carried out with an electromagnetic current meter Valeport® 801. In the case of SIU_{US}, the *h*/*Q* curve was obtained from hydraulic modelling for high discharges (i.e. by means of GUAD 2D® - for more details see supplementary material), and direct measurements using an electromagnetic current meter Valeport® 801 taken during baseflows. The hydraulic models were parameterized using high density topographic models (i.e. 1×1 m Digital Elevation Models obtained from RTK-GPS surveys) and bed roughness observations (i.e. grain-size distributions). Finally, in SIU_{DS}, the *h*/*Q* relation was built from direct flow-measurements by means of an aDcp (Sontek River surveyor M9®) during both floods and baseflows. To complete the *Q* series at ESE_{DS} and SIU_{DS} our data was combined with data provided by either the CHE in the case of Barasona and the Catalan Water Agency (ACA) in the case of Siurana for the dams' water releases.

3.2. Suspended sediment transport

Continuous records of suspended sediment concentration (hereafter *SSC*) were obtained indirectly through turbidity data, and complemented by means of manual and automatic water sampling. At those sites in which maximum *SSCs* was not expected to attain high values (i.e. ESE_{DS}, SIU_{US} and SIU_{DS}), turbidity was measured by low-range turbidimeters (McVann® ANALITE NEP-9350) with a measuring range of 0-3000 NTU ($\cong$ 3 g l^{-1}). Turbidimeters were equipped with an automatic wiper that keeps the lens clean. In ESE_{US}, maximum *SSCs* were expected to be higher (as in the neighbouring Isábena, as was reported by López-Tarazón et al., 2009) and, consequently, a high-range back-scattering turbidimeter (Endress+Hausser® Turbimax WCUS41) with a measuring range up to 300 g l^{-1} was installed. Campbell data-loggers (CR-200 and CR-500) were linked to the turbidity probes to record turbidity values every 15 min from 1-min average readings. Turbidity data was later converted into *SSC* by means of an on-site calibration procedure with water and sediment samples taken at the sections where turbidity probes were installed. Water and sediment samples were collected intensively during individual flood events and routinely during low flows either manually by depth-integrated sediment samplers or automatically by means of an ISCO® 3700. Samples were then labelled and brought to the laboratory where they were vacuum filtered using cellulose and glass microfiber filters (Filter-Lab, 0.0012 mm pore size). The filtered water volume was measured. Finally, all samples were dried and weighed to determine the suspended sediment concentration (*SSC*). The organic matter content was determined and subtracted from the final dried filter weight (for more details see Tena et al., 2011).

A statistical relation between turbidity (*NTU*) and *SSC* of all the samples taken was established for each turbidimeter. In the case of the low-range turbidimeters, calibrations followed a linear regression ($SSC = a \times NTU + b$, where a varies from 0.006 to 0.8275 and b from -0.0091 to 0.0015) with coefficients of determination (r^2) ranging between 0.81 and 0.98. In the case of the high-range turbidimeter the best fit to the data (r^2 = 0.91) was obtained by a second order polynomial regression ($SSC = 0.1736 \times NTU^2 + 0.781 \times NTU$). Due to instrumentation malfunctioning at ESE_{DS}, between 03/05/2013 and 30/09/2013, *SSC* was estimated from direct samples taken during flood events (i.e. every 15-min during the rising limb of the hydrograph and every 1-2 h in the falling limb) and weekly during baseflows. It is worth noting that only one flood occurred during the malfunctioning period (maximum *SSC* was around 0.58 g/l). For the rest of the period, both *Q* and *SSC* were usually very low (i.e. 0.03 $m^3 s^{-1}$ and 7 mg l^{-1}, respectively). These data were used to derive a continuous record applying a widely used interpolation methodology (e.g. Phillips et al., 1999; Rovira and Batalla, 2006; López-Tarazón et al., 2009) that assumes that a given *SSC* is representative of the intersampling period between samples (for which a linear interpolation is established).

3.3. Sediment load calculation

Suspended sediment load (*SSL*) is calculated at each monitoring site and for the whole study period by multiplying the records of *Q* and *SSC* obtained at 15 minute intervals. Subsequently, flow and sediment load duration curves were calculated with the cumulative percentage of runoff and *SSL* plotted on the Y-axis and the frequency of time for which each fraction of flow and sediment was equalled or exceeded on the X-axis.

4. RESULTS

4.1. Hydrology

The study period in ESE_{US} can be considered dry overall when compared to the long-term average runoff (555 hm^3 y^{-1} for the period 1949-2010; Fig. 2a). The first year was notably dry (342 hm^3) while the second year was more humid than the long-term average (706 hm^3; Table 1). Mean discharge (Q_{mean}) was 16 m^3 s^{-1}. Summer was the wettest season (374 hm^3), followed by spring (342 hm^3), autumn (214 hm^3) and winter (119 hm^3; Table 2). We have considered floods as the events in which discharge exceeds 1.5 times the baseflow at the beginning of the rainfall event. Based on this, a total of 37 flood events were observed during the study period. Maximum peak discharge (Q_{max}) ranged between 12 and 477 m^3 s^{-1} (i.e. Q_8, where Q_i is the discharge associated with a recurrence interval of *i* years). Similar patterns are observed downstream. The first year in ESE_{DS} was very dry, with a water yield of 9 hm^3 (87% below the average) as the dam gates were closed until January 2012. In contrast, the second year was humid (three events were recorded) with an annual runoff of 116 hm^3. Maximum instantaneous *Q* ranged from 24 to 411 m^3 s^{-1}.

Table 1.
Discharge and suspended sediment transport for the study period in the control and impact monitoring sites of the Ésera and Siurana rivers.

Site	Year	Q_{max}[a] (m^3 s^{-1})	Q_{mean}[b] (m^3 s^{-1})	Q_{min}[c] (m^3 s^{-1})	Total runoff[d] (hm^3)	SSC_{max}[e] (g l^{-1})	SSC_{mean}[f] (g l^{-1})	SSC_{min}[g] (g l^{-1})	Total load (t)
ESE_{US}	2011-12	195	10.81	1.02	342	24.700	0.258	0.000	166463
	2012-13	477	22.40	1.60	706	27.810	0.236	0.001	438043
	Study period	477	16.59	1.02	524[i]	27.810	0.247	0.000	302252[i]
ESE_{DS}	2011-12	0	0.30	0.30	9	0.029	0.006	0.001	52
	2012-13	411	3.68	0.30	116	2.610	0.011	0.000	11507
	Study period	411	1.98	0.30	63[i]	2.610	0.008	0.000	5780[i]
SIU_{US}	2011-12	22	0.11	0.02	3	2.481	0.007	0.001	367
	2012-13[j]	33	0.18	0.04	8	2.481	0.007	0.001	371
	Study period	33	0.14	0.02	5[i]	2.481	0.007	0.001	369[i]
SIU_{DS}	2011-12	2	0.17	0.00	5	0.129	0.003	0.000	14
	2012-13	5	0.16	0.01	5	0.891	0.004	0.001	51
	Study period	5	0.16	0.00	5[i]	0.891	0.003	0.000	32[i]

[a]*Maximum peak discharge*
[b]*Mean discharge*
[c]*Minimum discharge*
[d]*Total annual runoff*
[e]*Maximum suspended sediment concentration*
[f]*Mean suspended sediment concentration*
[g]*Minimum suspended sediment concentration*
[i]*Mean value*
[j]*Mean daily discharge was used instead of the 15-min values during 49 days*

Mean runoff in the Siurana upstream section (SIU_{US}) during the study period was lower than that obtained from the historical series (1991-2013; Fig. 2b). Water yield was lower in the first than in the second year (i.e. 3 and 8 hm^3, respectively), with an overall mean discharge of 0.14 m^3 s^{-1} (Table 1). Flow was characterized by a marked seasonality, with high Q occurring in spring and autumn (Q_{mean} of 0.27 and 0.16 $m^3 s^{-1}$, respectively; Table 2). Six events were recorded during the study period, with peak discharges ranging from 1.9 to 33 $m^3 s^{-1}$. In general, floods were flashy, with rapid Q peaks attained in only few hours. At the impact site (SIU_{DS}), both total runoff and Q were similar along the two years, averaging 5 hm^3 and 0.16 $m^3 s^{-1}$ respectively (Table 1). In this section, flow regime differs greatly from SIU_{US}, especially in summer, due to water being released from the dam for irrigation purposes. Here summer is the second wettest season, while in the upstream monitoring site it is the season with the least flow (Table 2). A total of 15 floods were observed, with maximum instantaneous values ranging from 0.4 to 5.3 $m^3 s^{-1}$. Floods are of substantially lower magnitude than those in $SIU_{US,}$ but with longer duration, and discharges remain around 2 $m^3 s^{-1}$ for several days or even weeks (Fig. 3). It is worth mentioning that 3 of the floods recorded during the second year came from the small tributary and not from the dam. Although no direct flow data from the tributary is available, maximum peak flows for those events at the monitoring site ranged from 2.6 to 4.1 $m^3 s^{-1}$.

Table 2.

Seasonal discharge and suspended sediment transport for the study period in the control and impact monitoring sites of the Ésera and Siurana rivers.

Site	Season	Q_{max}[a] ($m^3 s^{-1}$)	Q_{mean}[b] ($m^3 s^{-1}$)	Q_{min}[c] ($m^3 s^{-1}$)	Total runoff[d] (hm^3)	SSC_{max}[e] ($g\ l^{-1}$)	SSC_{mean}[f] ($g\ l^{-1}$)	SSC_{min}[g] ($g\ l^{-1}$)	Total load[h] (t)
ESE_{US}	Autumn	235	13.59	1.02	214	24.77	0.28	0.00	190213
	Winter	149	7.60	1.14	119	15.28	0.10	0.00	42322
	Spring	87	21.50	1.11	342	24.30	0.21	0.00	74216
	Summer	477	23.50	1.60	374	27.81	0.38	0.00	297755
	Study period	477	16.5[i]	1.02	1048[j]	27.81	0.24[i]	0.00	604506[j]
ESE_{DS}	Autumn	0	0.30	0.30	5	0.03	0.00	0.00	25
	Winter	75	0.60	0.30	10	2.61	0.00	0.00	775
	Spring	70	1.94	0.30	31	1.10	0.01	0.00	321
	Summer	411	5.02	0.30	80	0.58	0.01	0.00	10438
	Study period	411	1.96[i]	0.30	125[j]	2.61	0.01[i]	0.00	11559[j]
SIU_{US}	Autumn	17	0.16	0.03	2	2.48	0.01	0.00	246
	Winter	0	0.07	0.06	1	0.02	0.00	0.00	2
	Spring[k]	33	0.27	0.02	6	2.48	0.01	0.00	480
	Summer	0	0.09	0.02	1	0.25	0.01	0.00	11
	Study period	33	0.15[i]	0.02	11[j]	2.48	0.01[i]	0.00	738[j]
SIU_{DS}	Autumn	4	0.13	0.01	2	0.03	0.00	0.00	31
	Winter	0	0.02	0.02	0	0.01	0.00	0.00	1
	Spring	5	0.28	0.02	4	0.15	0.00	0.00	25
	Summer	4	0.22	0.00	3	0.40	0.00	0.00	8
	Study period	5	0.16[i]	0.00	10[j]	0.40	0.00[i]	0.00	65[j]

[a]*Maximum peak discharge*
[b]*Mean discharge*
[c]*Minimum discharge*
[d]*Total seasonal runoff*
[e]*Maximum suspended sediment concentration*
[f]*Mean suspended sediment concentration*
[g]*Minimum suspended sediment concentration*
[h]*Total seasonal sediment load*
[i]*Mean value*
[j]*Sum of the two-year period*
[k]*Mean daily discharge was used instead of the 15-min values during 49 days*

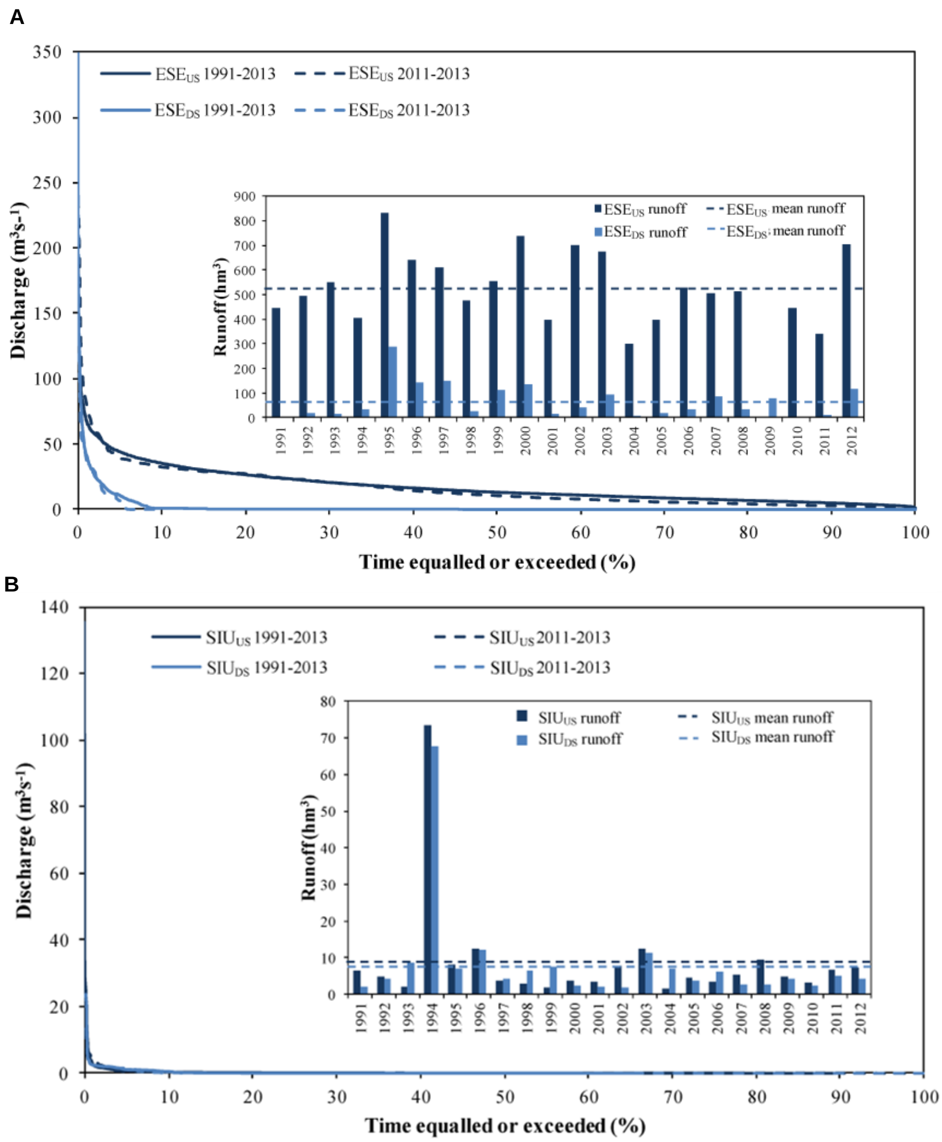

Figure 2. *(A) Flow duration curves calculated for the upstream and downstream discharges from the Barasona Reservoir (River Ésera), for the period 1991-2013, and for the study years (2011-2013). The input diagram shows the annual runoff for the period 1991-2013; (B) Flow duration curves calculated for the upstream and downstream discharges of the Siurana Reservoir (River Siurana), for the period 1991-2013, and for the study years (2011-2013). The input diagram shows the annual runoff for the period 1991-2013.*

4.2. Suspended sediment concentrations and loads

Figure 3 presents the hydrograph (*Q*) and sedigraph (*SSC)* for the whole study period at each monitoring site. Mean *SSC* (SSC_{mean}) at ESE_{US} was 0.25 g l^{-1} (Table 1), with the highest mean values observed in summer (0.38 g l^{-1}) and the lowest during winter (0.1 g l^{-1}; Table 2), following the observed seasonal pattern for runoff. Maximum *SSC* (SSC_{max}) reached 28 g l^{-1} during a flood event on the 21st of July 2013 (Q_{max} = 98 m^3 s^{-1}; Fig. 3a). Instantaneous *SSC* obtained during base-flows were remarkably variable due to the hydropeaking operations, ranging from less than 0.01 to more than 1 g l^{-1},

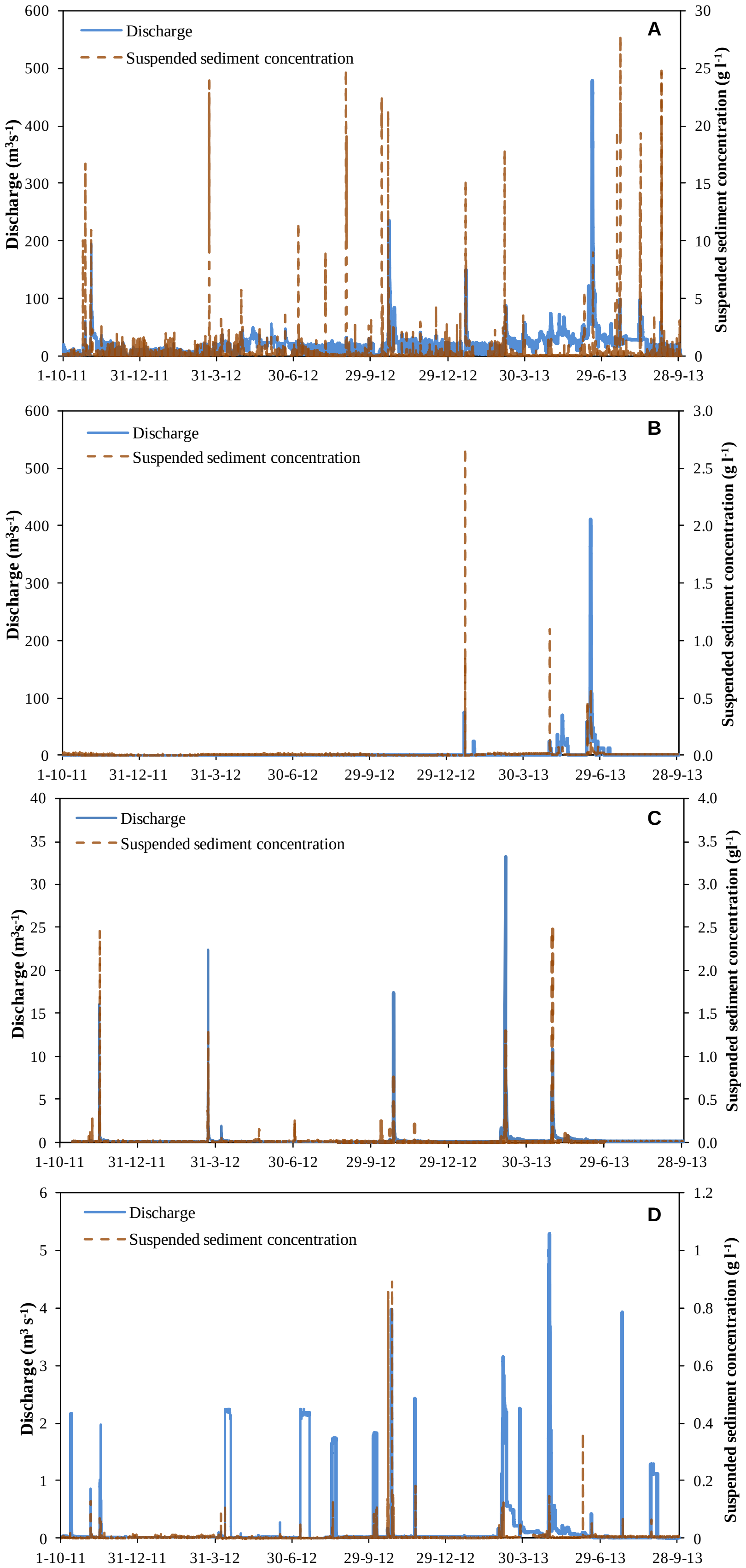

Figure 3. *Discharge and suspended sediment concentration recorded for the 2-yr study period in the River Ésera upstream and downstream the Barasona Reservoir (i.e. (A) ESE_{US}; (B) ESE_{DS}) and at the River Siurana upstream and downstream the Siurana Reservoir (i.e. (C) SIU_{US}; (D) SIU_{DS}).*

although substantially lower than the *SSC* observed during natural floods (Fig. 4). This fact reflects the role of sediment availability in the channel and the connectivity between sediment sources and the channel network that is only active during rainfall events and not during hydropeaking. Overall suspended sediment concentration and discharge were not correlated, as *SSC* of up to 4 orders of magnitude can be observed for the same *Q* (Fig. 5a). The suspended sediment load (hereafter *SSL*) averaged 302,252 t y^{-1}, giving a specific sediment yield (i.e. annual amount of sediment reaching the measuring section per unit of catchment area; hereafter *SSY*) of 337 t km^{-2} y^{-1}. For reference, the mean *SSY* in the River Isábena is 600 t km^2 y^{-1} for the period 2005-2010 (López-Tarazón and Batalla, 2014).

Sediment transport downstream from Barasona was completely different from that described upstream. A statistically significant correlation ($p<0.001$) between *SSC* and *Q* was found at ESE_{DS} for the study period (Fig. 5b). *SSC* values were significantly lower than that observed at ESE_{US}, with a SSC_{mean} of 0.006 g l^{-1} for the first year and 0.01 g l^{-1} for the second. SSC_{max} reached 2.6 g l^{-1} and was recorded for a *Q* of 75 m^3 s^{-1} (i.e. January 2013). In this case, *SSL* was completely associated with the occurrence of flood events, yielding 52 and 11,500 t during the first and second year, respectively, and with a mean *SSY* of 3.8 t km^{-2} y^{-1} (two orders of magnitude lower than that observed upstream).

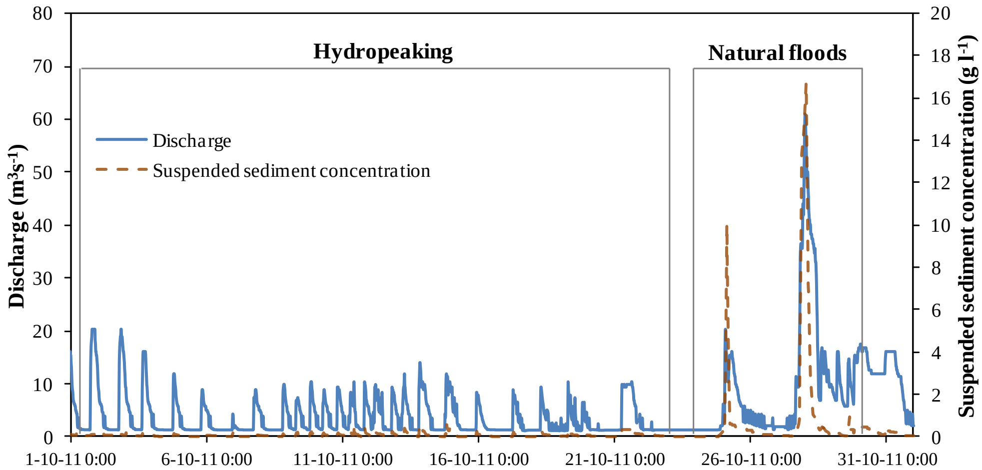

Figure 4. *Example of 1-month discharge and suspended sediment concentration at* ESE_{US} *(River Ésera upstream the Barasona Reservoir) to illustrate the role of hydropeaking on flow and sediment transport regimes, and the difference if compared with natural floods.*

The magnitude of *SSC* and *Q* in the Siurana was smaller given the different characteristics of this catchment when compared with the Ésera. *SSC* and *Q* relationships were also opposite to that observed in the Ésera, being statistically significant ($p<0.001$) only in the case of SIU_{US} (Fig. 5c). SSC_{mean} was 0.007 and 0.003 g l^{-1} upstream and downstream, respectively (Table 2). SSC_{max} measured at SIU_{US} was

2.5 g l^{-1}. This concentration occurred during two flood events (i.e. Q_{max} 16 m^3 s^{-1} in November 2011 and 10 m^3 s^{-1} in April 2013) for which the turbidimeter was out of range around 15% of the time, thus possibly underestimating the SSC_{max} and the *SSL*. At the seasonal scale, the *SSC* did not completely follow the pattern observed for runoff, although differences were small (Table 2).

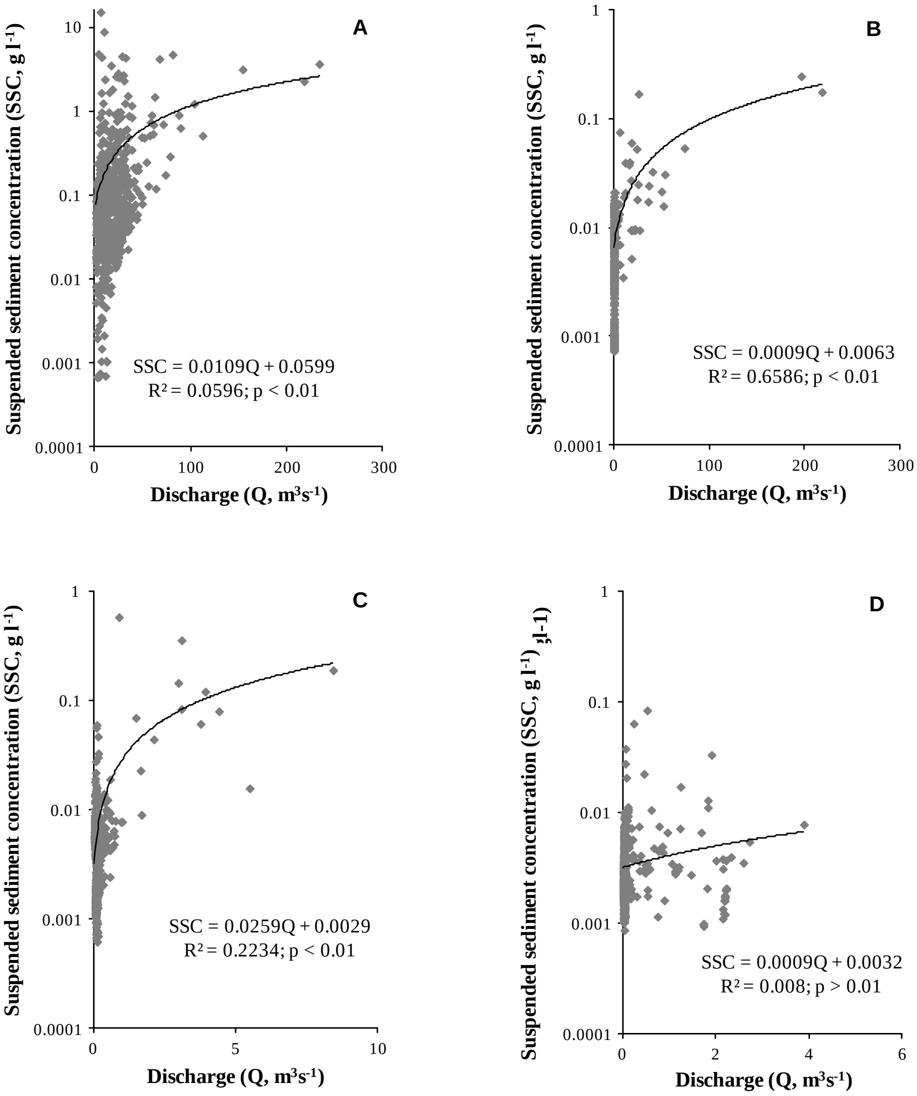

Figure 5. *Rating curve between mean daily discharge (Q) and mean daily suspended sediment concentration (SSC) at the ESE_{US} (A), ESE_{DS} (B), SIU_{US} (C) and SIU_{DS} (D) for the sampling period 2011-2013.*

Total *SSL* for the entire period was 738 t, averaging 369 t y^{-1}, and giving a *SSY* of 10.8 t km^{-2} y^{-1}. SSC_{max} at SIU_{DS} was 0.9 g l^{-1} and it was recorded during a flood coming from the small tributary after an intense rainfall episode (October 2012). *SSC* followed an independent pattern from *Q*, as it can be clearly appreciated in the figures 3d and 5d. In most of the floods, *SSC* was high only during very short periods of time (i.e. 1-2 h) and always at the beginning of the event, with a rapid decrease to pre-event values (i.e. around 3-4 mg l^{-1}). *SSL* shows a strong variability, yielding 14 t the first year and

51 t the second, giving a mean *SSY* of 0.45 t km^{-2} y^{-1} (1.5 orders of magnitude lower than upstream). However, the *SSL* of the second year would be dramatically reduced up to 27 t if the contribution of the tributary is not taken into account (i.e. the *SSL* estimated only for the tributary during that period is 24 t, yielding a mean *SSY* of 0.28 t km^{-2} y^{-1}).

4.3. Relation between runoff and sediment transport

There is no evidence of a seasonal correlation between *SSL* and runoff in the River Ésera (Fig. 6), a fact that suggests that the river's sediment load is probably more influenced by sediment availability than by flow discharge. In the upstream section summer and spring did not show any substantial difference concerning runoff although *SSL* was much higher during summer. This fact can be related to the source of runoff during the different seasons; in spring runoff mainly comes from snowmelt (usually with an associated low *SSC*) while in summer it is mostly generated after intense thunderstorms, likely producing large quantities of sediment from the badlands located in the central part of the catchment. Therefore, the highest *SSL* was mostly related to periods with frequent rainfall episodes leading to important flood events (summer and autumn) rather than periods which yielded large amounts of runoff but over longer periods of time (i.e. spring). In turn, no clear temporal pattern was observed downstream from the reservoir, as *Q* and *SSL* flowing through the river reach just depend on the operation of the dam, which is mainly focused on keeping the maximum water storage to ensure the supply to the Canal of Aragón and Catalunya. Almost all the runoff (hence *SSL*) is stored in the reservoir and derived through the Canal, and only 12 and 2% of the water and sediment supplied by the Ésera passed the dam during the entire study period. It is worth mentioning that the role of the dam in trapping sediment and water is in fact larger since in these estimates we have not taken into account the supply from the River Isábena.

Similarly, no clear seasonal relations between runoff and SSL were observed in the case of the Siurana upstream from the reservoir (Fig. 6). Spring was the wettest season followed by autumn, summer and winter. However, *SSL* was mainly transported during autumn and spring (i.e. 246 and 480 t, respectively) when most floods occurred. Furthermore, no yearly pattern between *SSL* and runoff (as in the Ésera) has been observed (Fig. 6). Runoff was considerably higher during the second year while *SSL* was similar in the two years, a fact that may suggest that the sediment load is limited by sediment availability in the basin and in the channel (i.e. sediment yield remains stable, no matter the total amount of runoff that is generated). Downstream from the Siurana dam, seasonal runoff was opposite to what could be expected under natural conditions, especially in summer, where the inflow into the reservoir is practically non-existent but the flow registered downstream is notably high. Runoff was hardly altered (i.e. reduction of 8%) in comparison with the water yield from the upstream reservoir. However, the effect of the dam on *SSL* is remarkable, with results indicating that the load at SIU_{DS} represents just 9% of the load upstream (i.e. 69 t in comparison to 738 t). *SSL* did not follow any clear seasonal pattern, while the variability between both years was quite important. Sediment load during the second year was almost four times higher than that observed in the first year, while runoff was practically the same. The different hydrological behaviour (i.e. magnitude, number and source of floods) of the two study years may explain the important interannual variability. In particular, the high load in 2012-2013 might be attributed to the role of the small tributary located between the dam and SIU_{DS}. The three floods from the tributary supplied 14% of the runoff and 50% of the annual *SSL* during that particular year, highlighting the importance of the tributary and almost the negligible sediment output from the dam.

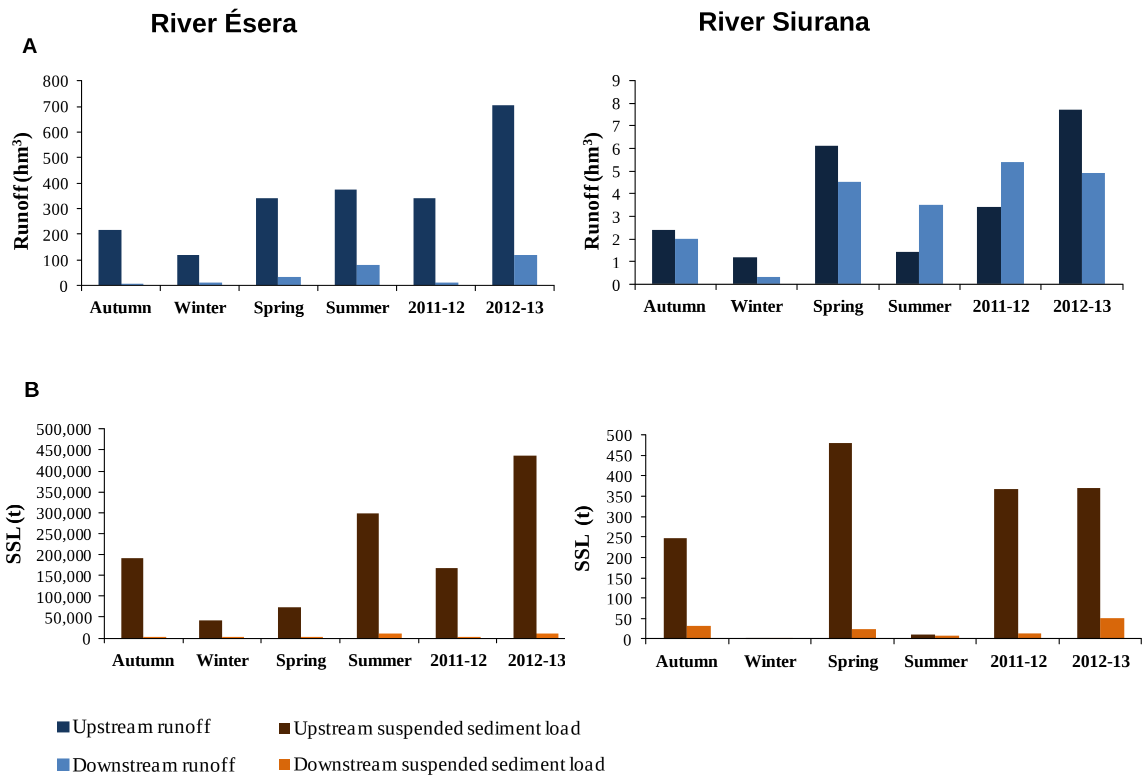

Figure 6. *(A) Water and (B) suspended sediment yields of the Ésera (left hand) and Siurana (right hand) rivers for the study period 2011-2013. Plots show the cumulative seasonal and annual results for each of the study sites (upstream and downstream of the respective reservoirs).*

4.5. Temporal distribution of sediment loads

The temporal distribution of a load during a given temporal scale (i.e. one year, a study period) can be examined by plotting the proportion of the cumulative loads versus the cumulative percentage of time (i.e. time required to transport a given proportion of the total load for a given temporal scale). The duration curves presented in Fig. 7 illustrate the distribution of the runoff and *SSL* during the study period. Different patterns can be distinguished between rivers and sites (Control -US and impact -DS).

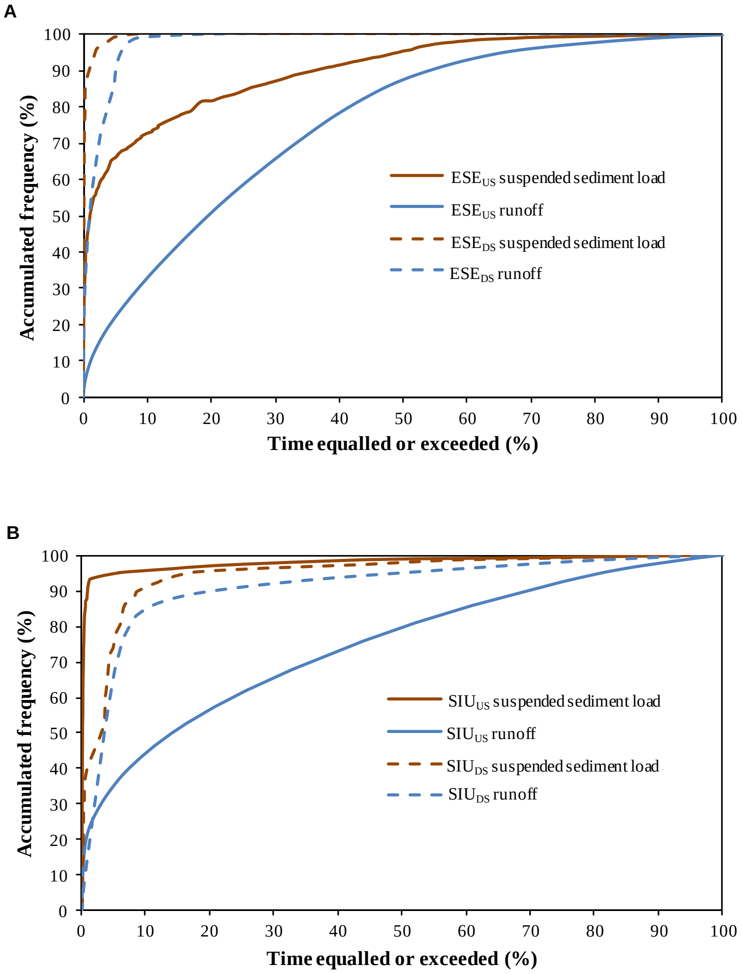

Fig. 7. *Suspended sediment load and runoff duration curves in the control and impact sites in the Ésera (A) and Siurana (B) rivers for the 2-yr study period (2011-2013).*

Runoff is more constant through time than *SSL* in ESE_{US}; 50% of the sediment was transported during just 1% of the time, while in the case of runoff, the same proportion was transported during 20% of the time. This difference is much more pronounced for both runoff and *SSL* at ESE_{DS}; discharge equalled or exceeded only 1% of the time was able to transport more than 90% of the sediment load and represented 50% of the annual water yield.

In relation to the River Siurana, regardless of the evident effect of sediment exhaustion on the sediment load, floods are still responsible for transporting most of the sediment at SIU_{US}. Flood events occurred 1% of the time and transported 92% of the sediment load but only 23% of the water. In the case of SIU_{DS} discharge equalled or exceeded 10% of the time transported 91% of the *SSL* and 86% of the runoff. Results indicate that overall most runoff and suspended sediment are transported during short periods of time, highlighting the strong Mediterranean character of the catchment; especially upstream from the dam i.e. the *SSL* curve in SIU_{US} is steeper than in SIU_{DS}. There, 80% of the *SSL* is transported during 1% of the time, while the same amount of time is responsible for 40% of the load in the section downstream. This fact indicates that in upstream reaches sediment transport is mostly controlled by flood events (regardless of sediment availability in the catchment), while downstream the transport remains more stable through time due to the presence of the dams, a behaviour that it is only altered by occasional responses from the tributary.

5. DISCUSSION

5.1. Flow and sediment transport upstream from reservoirs

The Ésera is a mountainous stream located in the northeastern part of the Ebro basin (i.e. Central Pyrenees) with a mean annual rainfall of 1,000 mm and a nivo-pluvial hydrological regime. Accordingly, high discharges typically occur in spring (due to snowmelt), and in late summer and autumn as a consequence of localized thunderstorms, as is shown in Fig. 6. The Siurana is located in the southeastern part of the Ebro catchment, an area highly influenced by the Mediterranean climate with an annual rainfall of 500 mm, a rainfall-based flow regime and a strong seasonality, with floods generally taking place in spring and autumn after intense thunderstorms. It is worth noting that both areas have been affected by extensive land use changes that have occurred during the last 50 years in the Iberian Peninsula (see examples of effects of land use changes on hydrology in Gallart and Llorens, 2004; Buendía et al., 2015). Natural afforestation following land abandonment has altered water and sediment supply from the catchments, a fact that likely affects the dynamics of what today we describe as control sites.

Overall, the flow regime is highly variable upstream from the Barasona Reservoir, with high discharges (i.e. taken here as those that double Q_{mean}) occurring 12% of the time (i.e. a total of 37 flood events occurred during the 2-yr study period). In contrast, the control site upstream from the Siurana Reservoir is characterized by flashy events with high discharges occurring 6% of the time (just 6 flood events occurred during the study period). Moreover, flood flows here return to baseflow shortly after the storm ends, while in the Ésera the falling limbs of the hydrographs are much prolonged in time. These hydrological differences reflect the characteristic sediment transport dynamics observed in both control sites. Despite the manner in which seasonality creates a bimodal *SSL* pattern in both rivers, in the case of the Ésera the difference between seasons are more pronounced and they are not related with the hydrological pattern (Fig. 6). There, 81% of the annual *SSL* was transported during autumn and summer. Runoff is high in spring, since it is controlled by the snowmelt, although *SSC*s are low and, consequently, sediment loads are also reduced. In contrast, at SIU_{US}, 98% of the sediment load (regardless of its magnitude) was transported during autumn and spring, and it is directly correlated with rainfall events (Fig. 6). Floods were responsible for 92% of the total *SSL* in SIU_{US}, and 70% in ESE_{US}, reflecting the different degree of Mediterranean influence on both catchments. Similar load duration to that observed in SIU_{US} have been reported in other Mediterranean catchments (e.g. Estrany et al., 2009). In contrast, the duration curve of the Ésera is much less steep (Fig. 7), a fact that also indicates the role of baseflows on the annual suspended sediment load (similar results were reported by López-Tarazón et al., 2011 for the neighbouring Isábena catchment where the distribution of sediment sources is similar to the Ésera). This fact is explained by: i) the high runoff volume flowing during spring due to snowmelt that despite carrying low *SSC* in comparison to that observed in summer and autumn, transports considerable amounts of sediment *SSL*; and ii) the high availability of sediment in the river (easily removable even for base flows; López-Tarazón et al., 2009) due to the presence of highly erodible badland strips in the middle part of the basin which are highly connected to the fluvial network. As indicated previously, this has been reported to be important for the annual sediment yield in the nested Isábena catchment (López-Tarazón et al., 2011; Piqué et al., 2014) and other Mediterranean mountain areas (e.g. Gallart et al., 2013) where the sediment dynamics are dominated by the badlands activity. The consequence of the different sediment availability existing at both catchments can be also observed in the *SSC*-*Q* relations, being statistically correlated at the Siurana but not in the Ésera, which shows a high degree of scatter between the two variables likely generating remarkable hysteresis effects (Walling, 1977; López-Tarazón et al., 2009).

The first monitoring year was dry in comparison to the long-term records in both catchments, while the second performed above the average. Accordingly, the sediment load was higher in the Ésera during the second year but this was not the case in the Siurana. This differential behaviour can be attributed to sediment availability. While the Ésera is a non-supply-limited system (although availability is variable throughout the year) whose sediment production is in the same order as the river's transport capacity, the Siurana basin is a limited system with small sediment supply, owing to the relatively low-intensity erosion processes in the area (thus *SSC* hardly reaches high values, no matter the magnitude of the flood events; Fig. 3). Sediment availability is also the reason for the huge differences in the specific sediment yield estimated in both rivers (337 t km^{-2} y^{-1} for the Ésera and 11 t km^{-2} y^{-1} for the Siurana). If compared with other Mediterranean counterparts, the Ésera performs in the higher band of *SSL*, whereas the Siurana belongs to the group of rivers showing low sediment yield values in the context of European watersheds (e.g. Inman and Jenkins 1999; Batalla et al., 2005; Batalla and Vericat, 2011; Vanmaercke et al., 2011; Gamvroudis et al., 2015).

5.2. Flow and sediment transport downstream from dams

Reservoirs trap most of the sediment and typically reduce flood magnitude and frequency. Annual runoff can also be affected by water diversions from the dam. This fact can be illustrated by our case study rivers, where the sediment load is reduced up to 90% in both rivers, but the total runoff is only reduced in the River Ésera. The load of nutrients and organic matter is typically associated with fine sediment in suspension, so its reduction may significantly alter the biochemistry of the stream courses and, hence has an effect on groundwaters and, further downstream, onto coastal zones (Tzoraki et al, 2007). High discharges are responsible for most of the sediment transport at ESE_{DS}. In this section most runoff and suspended sediment are delivered during short periods of time; e.g. discharges equalled or exceeded 1% of time were able to transport 91% of the fine sediment load and 50% of the annual water yield, while 99% of the sediment and 85% of the runoff was transported by discharges equalled or exceeded just 5% of the time (Fig. 7). Tena and Batalla (2013) described a similar pattern for several non-regulated rivers located in the southern Mediterranean region of the Ebro basin (ephemeral rivers with rainfall-based flow regime). These authors found that, for instance, floods in the River Matarranya occur less than 7% of the time and are responsible for more than 60% of the water yield, while 90% of the *SSL* was transported during less than 2% of the time. That comparison indicates that after regulation the hydrosedimentary behaviour of the Ésera resembles that observed in more arid areas, in which high magnitude low frequency floods are the dominant process for sediment and runoff delivery (e.g. Wolman and Miller, 1961; Coppus and Imeson, 2002; Tena and Batalla, 2013). Thus regulation increases the Mediterranean character of this Pyrenean river.

Regulation also affects the hydrology of the Siurana, i.e. despite the mean annual discharge and the total annual runoff remaining practically unaltered, the flow regime (seasonal distribution) and magnitude and frequency of floods were largely modified. Regarding seasonal runoff distribution, the reservoir inverts the natural regime of the river by keeping high flows during the summer (owing to irrigation and domestic demands in the coastal areas), despite inputs from the upstream sections being practically non-existent (i.e. the control site is almost dry during this season). Flow interruption has been considered as the most relevant feature controlling the aquatic fauna in temporary rivers (De Girolamo et al., 2014). Moreover, the flashy character of floods in SIU_{US} changes in the downstream section where flood magnitude is much lower (i.e. the maximum peak was reduced up to 80%) but hydrographs stay longer, lasting for several days and even weeks due to regulation (Fig. 3). Consequently the Siurana changes from a typical Mediterranean behaviour, both for runoff but also for sediment transport as results pointed out, to a more permanent and stable flow, i.e. more typically associated with basins of a less marked Mediterranean character.

The distinct effect of the two reservoirs over the respective basin's sediment load becomes evident when sedimentation rates are compared. Sedimentation in Barasona during the study period (only including the River Ésera) attained 300,000 t y^{-1} (Table 1); this figure would, however, increase up to 550,000 t y^{-1} (after López-Tarazón and Batalla, 2014) if mean sediment yield from the River Isábena would also be included. These values are in consonance with those previously reported by several authors who estimated, through different methodologies (e.g. sediment coring, bathymetrical surveys), that sedimentation ranged from 450,000 to 900,000 t y^{-1} (including both rivers, the Ésera and the Isábena e.g. Sanz-Montero et al., 1996; Valero-Garcés et al., 1999; Batalla and Vericat, 2011). It is worth to remark that the results here presented could be well underestimated due to the dryness of the first study year. Conversely, the average sedimentation rate in the Siurana reservoir is in order of 350 t y^{-1} (Table 1), three orders of magnitude lower than that reported for Barasona. Altogether corroborates results from Batalla and Vericat (2011) who concluded that the reservoirs located in the Pyrenean area (i.e. where Barasona is included) accumulate up to five times more sediments than those located in the southern Mediterranean area (i.e. where Siurana is located). This fact emphasizes the distinct hydro-sedimentary behaviour of the two catchments, owing to their different hydro-climatic characteristics and catchment properties.

It is well-known that the most important flow alteration due to regulation in Mediterranean Rivers is the reduction of flood magnitude (Batalla et al., 2004; Kondolf and Batalla, 2005). As a consequence, river channels quickly stabilize and experience a reduction in both active channel width and geomorphological activity and complexity, i.e. in the absence of competent floods the riparian vegetation is able to colonize gravel deposits previously active (e.g. Batalla et al., 2006; Nelson et al., 2013; Lobera et al., 2015). Together, this contributes to the environmental degradation of the fluvial ecosystem and reduces the habitat for aquatic and riparian wildlife (e.g. Graf, 2006; Magdaleno et al., 2012). Mediterranean rivers have enormous biodiversity with high levels of endemism adapted to a high seasonal variability (flooding in the wet season and drought in the dry season) and high levels of landscape heterogeneity (Gasith and Resh 1999; Bonada et al., 2007b; Koniak and Noy-Meir, 2009). Thus, regulation, by changing the hydrosedimentary regime, likely affects rivers' ecological functioning and biogeochemical cycles (Tzoraki et al., 2007; Ponsatí et al., 2014).

6. CONCLUSIONS

This paper describes the sediment transport observed in two regulated rivers in the Western Mediterranean region, assessing the influence of the reservoirs on their hydrosedimentary regimes. The rivers Ésera and Siurana were selected to represent both the humid (mountainous) and the semiarid characters of rivers in the region. Overall results indicate that reservoirs cause a marked shift in their hydrosedimentary behaviour. The main findings of the study can be summarised as follows:

i) Reservoirs in the rivers Ésera and Siurana reduce the sediment load by 2 orders of magnitude at the downstream monitoring sites, although the total runoff is only reduced in the case of the Ésera.

ii) The largest proportion (> 90%) of the suspended sediment load in the River Siurana upstream from the dam is mostly transported by occasional flash floods, despite instantaneous concentrations remaining rather low, owing to the low-intensity erosion processes in the catchment. In contrast, instantaneous concentrations in the Ésera are very high (of the order of tens of g l^{-1}) but floods are still responsible for 2/3 of the annual load, a fact that points out the important role of baseflows in the export of sediment from the basin.

iii) Differences in both sediment concentration and yield in the two rivers are attributed to the respective basins' sediment availability, with the Ésera having an unlimited supply, whereas the Siurana responds as a limited supply system in which suspended sediment never reaches high values no matter the magnitude of the flood events.

iv) The Barasona Reservoir alters the hydro-sedimentological behaviour of the river Ésera shifting from a humid mountainous regime to a semi-arid climate type of river, in which most of the sediment load is associated with few flood events (in this case, dam releases). In the case of the Siurana, the reservoir exerts the opposite effect, changing the sediment and flow regimes of the river from a typical Mediterranean behaviour to a more permanent and stable flow typical of less-arid regions.

Our results corroborate that reservoirs alter the hydrosedimentary regimes of fluvial systems; but the magnitude and frequency in which water and sediment transfer are modified is highly variable between catchments, being largely dependent on the upstream flow regime, and the size of the reservoir and dam operation. The upstream sediment supply has been also proven to be a relevant factor, together with the eventual sediment contribution from small tributaries downstream. Therefore, water and sediment management strategies in regulated rivers require a specific assessment of these particular factors in order to optimise water use and reduce downstream effects on river's functioning.

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Chapter 5

Bed disturbance below dams: observations from two Mediterranean rivers

The objective of this chapter is to analyse bed disturbance patterns upstream and downstream from dams in two Mediterranean rivers with contrasting flow regimes. The chapter contains the following submitted paper:

Lobera G, Andrés-Domenech I, López-Tarazón JA, Millán-Romero P, Vallés F, Vericat D, Batalla RJ. 2016. Bed disturbance below dams: observations from two Mediterranean rivers. Land Degradation and Development (accepted). *Impact factor (2015):* 8.145; *Area:* Environmental Sciences; *Quartile:* 1st.

Summary: Intra- and inter-annual bed disturbance patterns and their relations with flow magnitude are analysed in two Mediterranean regulated rivers (i.e. the Ésera and Siurana) during two years. Specifically, flow hydraulics, channel topography, bed mobility and bed material characteristics are analysed upstream and downstream from Barasona (river Ésera) and Siurana (river Siurana) dams. Results improve our understanding of channel disturbance via the application of different approaches, both in the spatial and temporal scales, used to characterize flow competence, particle entrainment including the travel distance of tagged particles, and the volumes of sediment eroded and deposited.

Keywords: Flow regime, dams, bed disturbance, sediment mobility, Mediterranean rivers.

ABSTRACT

River bed disturbance and associated sedimentary processes such as particle mobility are central elements to assess river ecosystem functioning. Dams change river dynamics and so affect the magnitude and frequency of biophysical elements (habitats) that depends on them. This paper examines the effects of two dams different in size, management and location, on the flow regime, flood competence and bed disturbance (including topographic changes and bed mobility) in two contrasting Mediterranean rivers, the Ésera and the Siurana. For this purpose, two reaches on each river were monitored upstream and downstream from reservoirs. Several monitoring and modelling techniques were used to characterize flow competence, particle entrainment, and the volumes of sediments eroded and deposited after floods. The flow regime of the Ésera has been modified from nivo-pluvial regime, typical of humid mountainous environments, to that observed in dry-semiarid regions, in which high magnitude but low frequency floods are the dominant processes. In contrast, the flow regime of the Siurana has changed from a typical Mediterranean stream to a regime observed in more temperate environments, with more permanent and stable flows. Changes in flow and flood regimes have affected channel morphodynamics downstream from the dams. Both rivers show notably physical changes, with channels clearly less dynamic below the dams. The lack of competent flows together with the sediment deficit associated with the dams has led to less active fluvial environments (i.e. reduced particle mobility and bed scour dynamics), a fact that affects instream habitat structure (i.e. more uniform grain size distribution, less physical heterogeneity and more stable flows).

1. INTRODUCTION

Runoff and erosion control the supply, transport and redistribution of sediment loads along river networks (from production to deposition zones) and, ultimately, contribute to the global earth denudation cycle. River forms and processes are mostly controlled by the sediment supply and the hydraulic action of the flow that cause bed-material entrainment and transport, a phenomenon that, in turn, is essential to generate and maintain the physical habitat of river ecosystems (Tuset et. al., 2015; Demissie et al., 2016).

Sediments entrain when discharge exceeds a given threshold, causing scour and deposition and associated morphological changes. The magnitude and frequency of these physical perturbations are determined by the hydrology of the upstream catchment and the forces exerted by running waters on the riverbed and banks. Bedload is the consequence of the flow forces acting on the bed and the resistance posed by the particles that rest on it. Overall, bedload typically represents a small part of a river’s total load, but its dynamics control channel morphology and are crucial for the maintenance of ecosystem functioning. Bedload is influenced by different elements that characterize river channels: i) particle parameters (grain-size, shape, and roundness), ii) bed structure (exposure and packing) and iii) bed morphology (Hassan, 1993; Green et al., 2015). Numerous studies have analysed the factors controlling bed-material entrainment and transport, but its dynamics (i.e. magnitude, variability) remains still rather unknown (e.g. Parker, 2011). As stated, the physical arrangement and the mobility of bed particles are of great ecological importance guaranteeing the structural features of the fluvial systems (e.g. Kondolf, 1997; Petts and Gurnell, 2005; Cienciala and Hassan, 2013).

Dams alter river flow regimes, particularly modifying the magnitude and frequency of floods, thus affecting the associated downstream morphosedimentary dynamics (e.g. Petts, 1984; Wolman and Williams, 1984; Batalla et al., 2004; Lobera et al., 2015). Dams also interrupt the longitudinal continuity of the river, affecting flow conveyance, sediment transport and its associated processes. Dams retain all bedload as well as a large proportion of the suspended load (Vericat and Batalla, 2006; Tena et al., 2013). As a consequence, river-channels downstream degrade (i.e. inside) and, over time, a complete transformation of the channel morphology according to the new sediment transport regimes occur (Petts and Gurnell, 2005). A large number of studies have identified a variety of geomorphic changes downstream from dams. According to Graf (2006) these are usually associated with: i) sediment-related effects as for instance bed scouring and armouring downstream from dams (e.g. Cahdwick, 1978; Vericat et al, 2006), ii) change of specific fluvial features; for example, rapids became more stable (e.g. Graf, 1980; Dolan and Howard, 1981; Kieffer, 1987); and iii) effects on river channel planform, as for instance vegetation encroachment affecting channel geometry and decreasing sediment availability (e.g. Surian and Rinaldi, 2003; Graf, 2006). All these morphological adjustments entail important ecological consequences; for instance, sediment coarsening reduces habitat availability, a fact that modifies the reproduction conditions for fish (Grams and Schmidt, 2002). Riparian species and floodplain ecosystems are also affected by the loss of lateral mobility and the deficit of sediment (Rollet et al., 2014).

Mediterranean climate is defined by marked precipitation and temperature patterns; hence, Mediterranean rivers often present low discharge (or even none) during the dry seasons but flashy flood events are observed during rainy, wet periods. Such natural disturbances pose an evolutionary pressure and control the channel processes and the ecological aspects of river channel form. In Mediterranean regions water availability and demand are out-of-phase most of the time. As a result, a large number of dams have been built during the 20th century to ensure water availability and reduce its temporal variability. For example, Spain (whose climate is mostly Mediterranean) has ca. 1150 large dams, more than any other country in Europe (Batalla and Vericat, 2010), and occupying the third position in the global ranking. These dams have the capacity to impound the 56% of the total annual runoff in the country.

Within this context, the present paper assesses physical river bed disturbance in two Mediterranean river reaches downstream from large dams. Riverbed dynamics are compared with their respective upstream counterparts. Channel topography, flow hydraulics, bed-material characteristics and bed-material mobility are analysed in the Ésera and the Siurana rivers during a 2-year period (2011-2013). The two rivers display distinctly different Mediterranean flow regimes (i.e. from mountainous humid to dry semiarid). Results offer new insights to understand the physical alterations into these fragile ecosystems after dam construction.

2. STUDY RIVERS

This research has been developed in four different river reaches within the Ebro catchment (NE Iberian Peninsula), two located in the River Ésera (upstream and downstream of the Barasona Reservoir; central-eastern Pyrenees), and two located in the River Siurana (upstream and downstream of the Siurana Reservoir; Catalan Coastal Range; see Fig. 1).

The River Ésera is a mesoscale Pyrenean catchment (1,500 km^2), the 83% of which is occupied by forests and natural vegetation (data from Corine Land Cover, 2006). It belongs to the Continental Mediterranean domain, with mean annual precipitation of 1,069 mm (ranging from >2,500 mm y^{-1} in the summits to 420 mm y^{-1} in the lowlands). The hydrology is characterized by a nivo-pluvial regime, with floods normally taking place in spring mainly controlled by snowmelt, and in late summer and autumn as a consequence of localized thunderstorms.

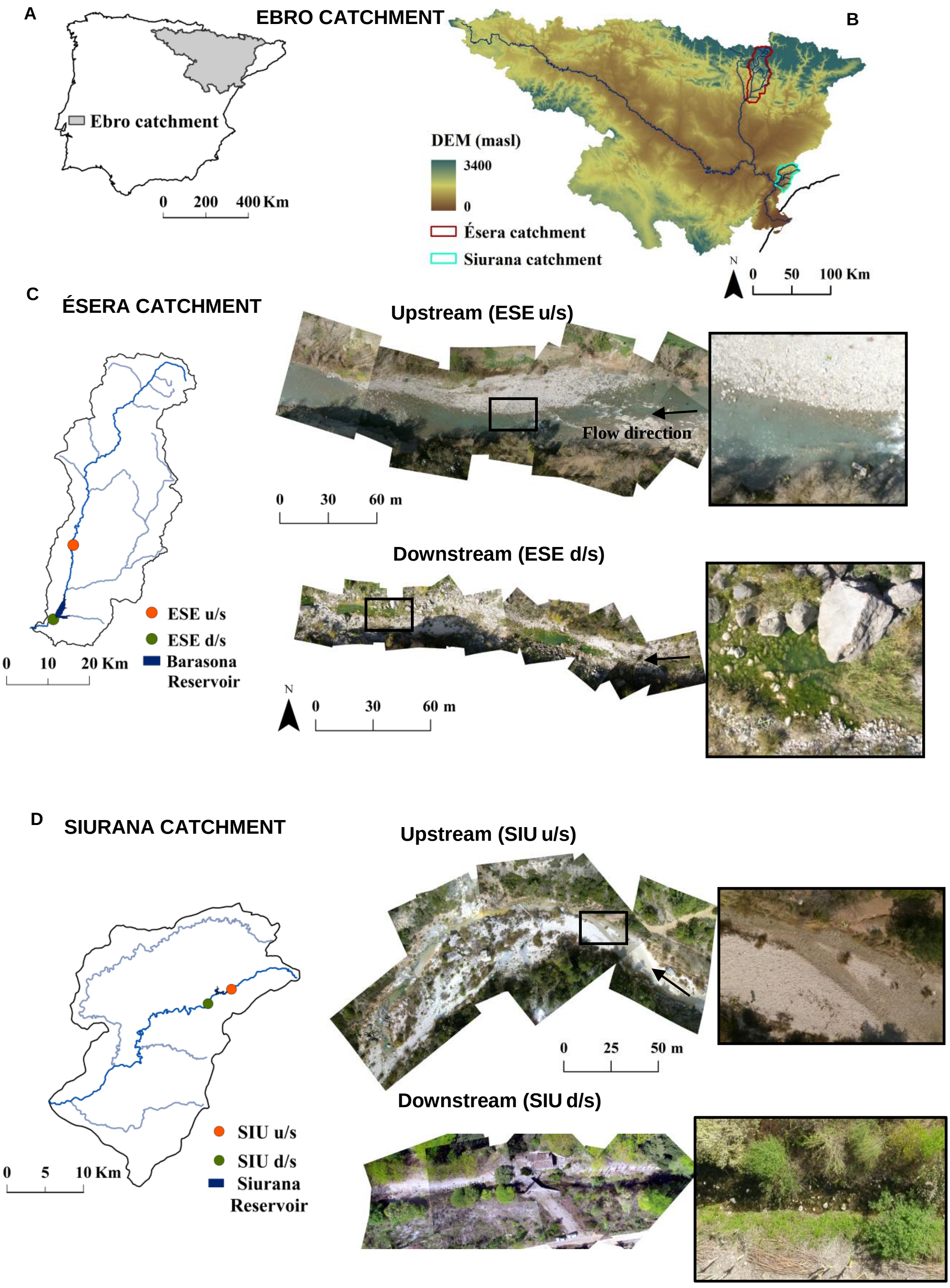

Figure 1. *(A) Location of the Ebro catchment in the Iberian Peninsula; (B) Location of the Ésera and Siurana catchments within the Ebro basin; (C) Location of the two study reaches located upstream (ESE u/s) and dowsntream (ESE d/s) of the Barasona Reservoir in the Ésera catchment; and aerial photograph of both upstream and downstream reach; (D) Location of the two study reaches located upstream (SIU u/s) and dowsntream (SIU d/s) of the Siurana Reservoir (Siurana cachment); and aerial photograph of both upstream and downstream reaches.*

The River Ésera is impounded by the Barasona Reservoir that is located near the outlet of the river (Fig. 1). It was built in 1932 to supply water to the Canal of Aragón and Catalunya that irrigates more than 100,000 ha of land. Its storage capacity is 92 hm^3, impounding 15% of the mean annual runoff that flows into it (Batalla et al., 2004). The reservoir collects water from the River Ésera and its main tributary, the Isábena (representing 75 and 25% of the runoff entering the reservoir, respectively). The upstream study reach (hereafter ESE u/s) is located 10 km upstream of the dam, near the village of Besians (Fig. 1). Mean discharge (hereafter Q, measured at the Graus gauging station, EA013, located halfway between ESE u/s and the dam, that is operated by the Ebro Water Authorities) is 17.6 m^3 s^{-1}, while the maximum instantaneous discharge (Q_{ci}) ever measured (August 1963) was 995 m^3 s^{-1} (a discharge with a return period of >100 years, Q_{100}, calculated by the Gumbel method from the series of Q_{ci} for the period 1949-2007). The downstream reach (hereafter ESE d/s) is located 500 m below the dam (Fig. 1). Flow is low and stable during most of the time at around 0.3 m^3 s^{-1}. The maximum discharge ever recorded was 505 m^3 s^{-1} in 1997 (corresponding to a recurrence interval of approximately 100 years, Q_{100}, calculated by the Gumbel method from the annual maximum daily discharge for the period 1992-2012). If the daily discharge records of both reaches for the period 1991-2013 are compared, it can be observed that the dam has reduced the Q (from 18 to 0.3 m^3 s^{-1}) and both the frequency and magnitude of floods (floods >40 m^3 s^{-1} have decreased from 7 to 1.5 per year, while the maximum discharge of the annual flood from 100 to 80 m^3 s^{-1}). Moreover, during the study period, Barasona Reservoir generated a reduction of the runoff around 90% (from 524 hm^3 to 63 hm^3; Fig. 2 and of the suspended sediment load around 98% (from 302,252 t to 369 t; Lobera et al., 2016). Concerning to the fluvial geomorphology, ESE u/s is a 200 m long and 43 m wide river-reach, with a mean slope of 0.006 m m^{-1}; the channel is a combination of different hydromorphological units, including step-pools, riffles, runs and rapids (as per Montgomery and Buffington, 1997). It is dominated by gravel and cobbles (median particle size D_{50} = 98.8 mm) although several patches of bedrock and fine sediment (silt and clay) can be also observed. In contrast, ESE d/s presents a length of around 160 m, 14 m of width and a mean slope of 0.008 m m^{-1}; the channel only presents one single hydromorphological unit (i.e. plane bed, Fig. 1), and is mainly composed by boulders and cobbles (D_{50} = 141 mm).

The River Siurana (southeast of Ebro basin; Fig. 1) drains an area of 610 km^2, 49% of which occupied by forests and natural vegetation and the rest by agricultural land (data from Corine Land Cover, 2006). The predominant land use of the headwaters (i.e. 73 km^2, upstream from the Siurana Dam; Fig. 1) is forest and natural vegetation, representing 81% of its total area. Mean annual precipitation is 500 mm (ranging from 400 to 700 mm), being characterized by the heavy thunderstorms that usually take place in spring and autumn. The Siurana has a typical rain-fed flow regime with a marked seasonality, even drying up during summer. The Siurana Reservoir (total storage capacity of 12 hm^3) was built in 1972 for irrigation and water supply, impounding up to 2.7 times the mean annual runoff that flows into it. The upstream section (hereafter SIU u/s) is located 1 km upstream from the reservoir (Fig. 1). Q is 0.14 m^3 s^{-1}, while the Q_{ci} ever measured was 33 m^3 s^{-1} on March 2013 (i.e. Q_4 according to the data from the Centre for Studies and Experimentation of Public Works -CEDEX). Finally, the last study reach (hereafter SIU d/s) is located at around 2 km downstream of the dam (Fig. 1). Q is 0.16 m^3 s^{-1}, similar to the value of SIU u/s. However, although mean flows are similar, the magnitude of floods have been substantially reduced (e.g. for the period 2011-2014, Q_{ci} is reduced from 33 to 5 m^3 s^{-1}). Flood frequency has also been modified below the dam, increasing from 3 to 6 floods per year (on average). Seasonal variability of the river flow has been also altered, especially in summer, when the discharge downstream is the highest of the year following water releases for irrigation purposes (Fig. 2), whereas SIU u/s maintains marginal flows. Furthermore, the Siurana Reservoir has not altered practically runoff (5 hm^3), whereas has reduced the suspended sediment load up to 90% (from 369 t to 32 t) during the 2-yr study period (Lobera et al., 2016). As in the case of the Ésera, both sections differ morphologically. The SIU u/s reach has a length of around 200 m, a width of 8 m and a mean slope of 0.016 m m^{-1}. It is a typical pool-riffle section, dominated by sands and gravels, being the sands mostly present in the pools and the plane bed (D_{50} = 9 mm), and the coarser particles (D_{50} = 51 mm) in the riffles. Finally, SIU d/s has a length of around 110 m, a width of 5 m and a mean slope of 0.008 m m^{-1}. Here the river is a plane-bed (it just presents one single hydromorphological unit) mainly composed by pebbles and cobbles (D_{50} = 52 mm).

The different characteristics of these two rivers provide a unique opportunity to study how much contrasted hydrological regimes and changes on flood frequency and magnitude in two impounded Mediterranean Rivers can have distinct effects on the channel disturbance patterns downstream from dams.

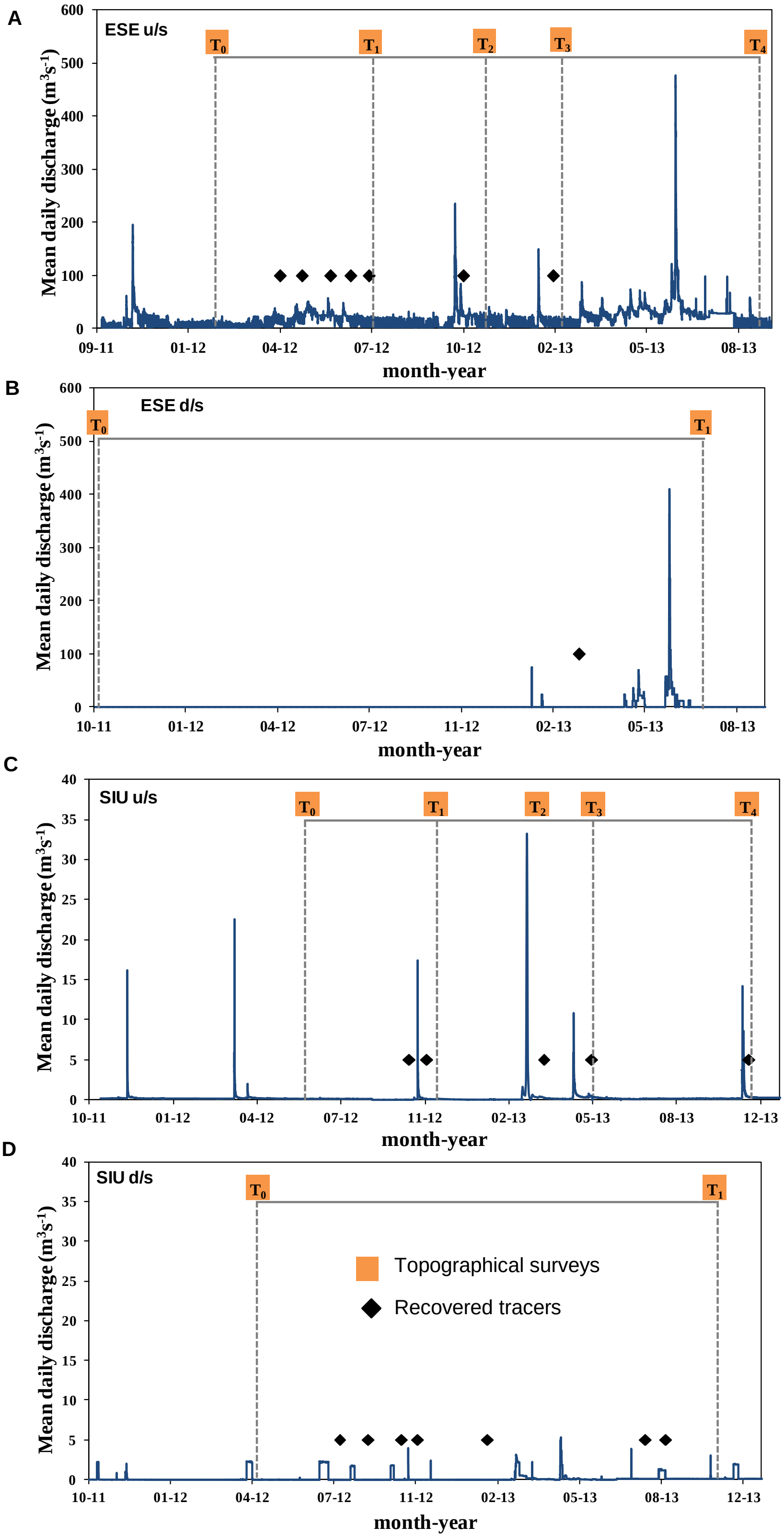

Figure 2. *(A) Discharge recorded for the study period in the River Ésera usptream the Barasona Reservoir (ESE u/s); (B) Discharge recorded for the study period in the River Ésera downstream from the Barasona Reservoir (ESE d/s); (C) Discharge recorded for the study period in the River Siurana upstream the Siurana Reservoir (SIU u/s); (D) Discharge recorded for the study period in the River Siurana downstream from the Siurana Reservoir (SIU d/s).*

3. METHODS

In order to examine the effects of regulation on bed disturbance at different spatial and temporal scales, a methodological approach that comprises the monitoring and modelling of four main components was used: 1) Channel topography (to calculate erosion and deposition associated to competent events), 2) Flow hydraulics (to estimate flow competence), 3) Bed-material (to characterise sediments grain-size), and 4) Bed mobility (to assess thresholds of particle entrainment and step-lengths). The most suitable and appropriate methods for each component, mainly depending on the individual characteristics of each site were used. Below we present the specific methods used in each component. The complete methodological design is presented in Fig. 3 whereas all details are provided in the following sections.

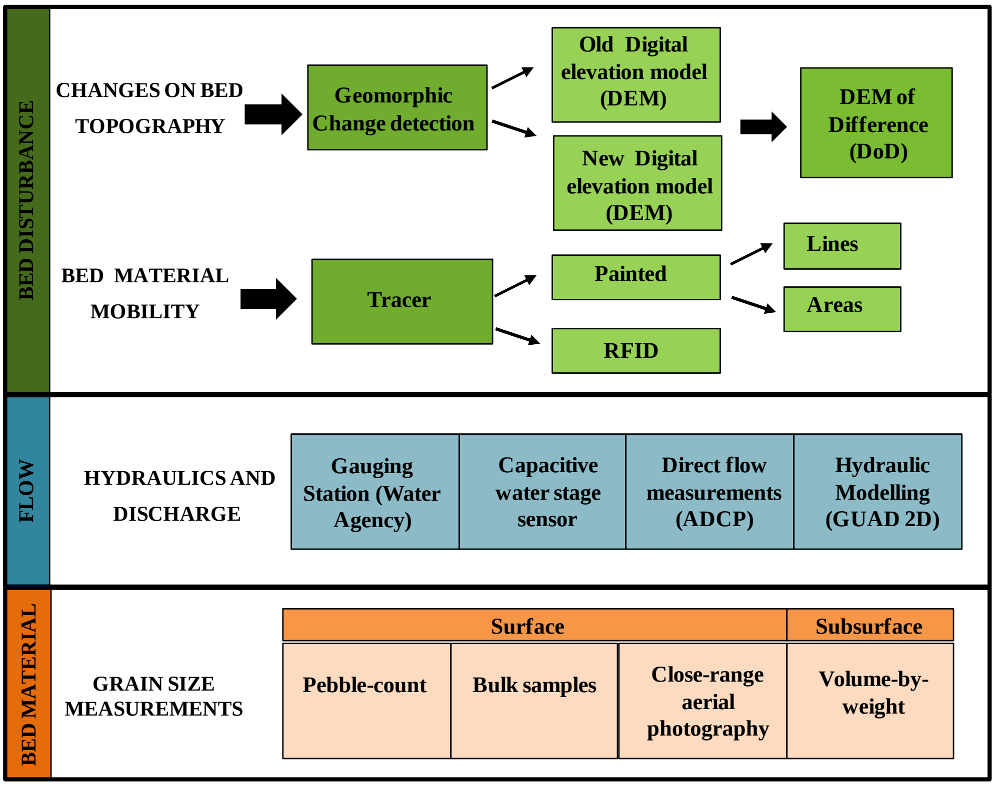

Figure 3. *Methodological approach followed for the analysis of flow and flood hydraulics, bed-materials and bed disturbance.*

3.1. Channel topography

Channel topography was used to 1) parameterize the hydraulic models (see section 3.2), and 2) study the topographic changes related to flood events. In the two sections located upstream from the dams (i.e. ESE u/s and SIU u/s), high density topographical surveys were carried out after almost all competent floods events (i.e. T_0, T_1, T_2, T_3 and T_4 in Fig. 2). In some occasions this was not possible because flows were relatively high and the channel was not wadable. In contrast, downstream from the dams (i.e. ESE d/s and SIU d/s), only two topographical surveys were conducted (i.e. T_0 at the beginning and T_1 at the end of the study period; Fig. 2). The different surveying frequency was due to the fact that during the study period only one flood occurred in ESE d/s, whereas several non-competent events were recorded in SIU d/s.

3.1.1. Data acquisition and digital elevation models (DEMs)

Topographical surveys were performed by combining data obtained by means of a Leica® Viva GS15 GNSS/GPS and a Leica® TCRP1201 Robotic Total Station in the submerged areas, and data acquired by a Terrestrial Laser Scanning Leica® ScanStation C10 in the exposed (dry) areas. Four ground control points (benchmarks) were positioned in each study reach. These determined the survey network control used to register all topographic data to the same coordinate system. The coordinates of these control points were obtained by the Leica® Viva GS15 GNSS/GPS and subsequently post-processed by means of the RINEX data registered in reference stations of the 'Geographic Institute of Aragón' and of the 'Cartographic and Geological Institute of Catalonia' for the Ésera and Siurana catchments respectively. Data post-processing allowed the correction of the coordinates, decreasing the errors of these to values less than 2 cm (3D quality, integration of the errors on position -X and Y- and elevation -Z-). These control points were used to set up a local base for the GPS. This base sent real time correction while surveying. The 3D quality of the observations never exceeded 5 cm. In case that the satellite reception was poor, observations were surveyed by means of the Total Station. The Total Station was set up and orientated by means of the ground control points. The point density of the surveys ranged between 0.5 and 3.4 points m^{-2}. The distribution of the collected points throughout the reach was based on a quasi-systematic method in which individual bed and bar units were surveyed in tightly spaced transects (e.g. Brasington et al., 2000). However, the high water levels in ESE u/s restricted the fieldwork in one occasion (T_3), when it was possible to survey only the lateral bar (i.e. 3,000 m^2). The Terrestrial Laser Scanning was set up and orientated by means of a floating network control (i.e. 4 HDS targets) surveyed with the Total Station. Data was decimated and regularized at a resolution of 1×1 meter using the freely available TopCat geostatistical toolkit (Brasington et al., 2012; included in the Geomorphic Change Detection Software, see http://gcd.joewheaton.org).

Digital Elevation Models (DEMs) were elaborated integrating the different topographic surveys. First, Triangular Irregular Networks (TINs) are created using ArcMap. TINs were subsequently converted to raster at 1-m grid resolution. DEM quality can be potentially affected by the interpolation and other factors, including survey point density quality, surface composition and topographic complexity (e.g. Wheaton et al., 2010).

There are a variety of ways to quantify and take into account this error. In this study we assessed the error by means of checkpoints that were not included in the elaboration of the DEMs. Five percent of the observations were removed from the data set before the DEM was elaborated and used as check points. They were intersected with the DEM and both elevations compared (one subtracted by the other; i.e. residuals). The mean absolute value of these was considered as the error of the DEMs at a given period (E_{DEMi}), and it was used later in the uncertainty analyses when the DEMs were compared (see section 3.1.2).

3.1.2 Topographic changes: DEMs of Difference (DoD)

DoDs were calculated from successive DEMs. The number of DoDs varies between reaches in relation to the number of surveys that were performed (Fig. 2). In the unregulated reaches, 4 DoDs were obtained, while downstream from the dams only one DoD was performed. The DoDs were used to represent the magnitude, direction, and distribution of changes in the channel bed after competent flood events. Data uncertainty was taken into account by means of the assessment of a minimum level of detection (minLoD) based on the errors on the DEM. This minLoD was calculated (after Brasington et al., 2003) as:

[1] $$minLoD = t\sqrt{(E_{DEMi})^2 + (E_{DEMi+1})^2}$$

where $E_{DEM\text{-}I}$, and $E_{DEM\text{-}i+1}$ are the error of the DEM of the period *i* or *i*+1, respectively, and *t* is the critical t-value at a chosen confidence interval level. In this paper, we used a confidence interval of 80% (t =1.282) following the discussion by Brasington et al. (2003). The values of the DoDs were compared (cell by cell) to the minLoD. When the topographic change (in absolute terms) in a cell was smaller than the minLoD, it was considered uncertain, while they were considered real when the changes were greater than the minLoD at the defined confidence interval. Thresholded DoDs (DoDs only presenting values >minLoD) were produced, from which total erosion, total sedimentation, and the net change were obtained.

3.2. Hydrology and hydraulics

Different sets of hydrological and hydraulic data have been used in this paper (Fig. 3). First, continuous *Q* records were obtained at the official gauging stations which are operated by the Ebro Water Authorities (hereafter CHE), in the case of the Ésera, and by the Catalan Water Agency (hereafter ACA), in the case of the Siurana. Secondly, at those sections were official gauging stations were not available, continuous *Q* records were obtained by *in-situ* monitoring and measurements; hydraulic data were regularly obtained from direct gauging at all the study sites. Finally, flow hydraulics was simulated by means of 2D modelling. Specific details are provided in the following sections.

3.2.1. Discharge

At ESE u/s, *Q* was provided by the CHE (EA013; Fig. 1), which measures water stage (*h*) continuously. At all the other sites (i.e. ESE d/s, SIU u/s and SIU d/s), water stage was measured every 15-min using capacitive water stage sensors (TruTrack® WT-HR). At-a-site stage-discharge relationships (*h/Q*) were obtained for each monitoring section by combining direct measurements, modelling outcomes (see section 3.2.2) and data from the nearby hydrometric stations. The rating curve of ESE d/s was elaborated from direct *Q* gauges by means of an electromagnetic current meter Valeport® 801. In the case of SIU u/s, *Q* was obtained from direct measurements (Valeport® 801) for medium and low flows and from hydraulic modelling (i.e. GUAD 2D®, see 3.2.2) for high *Q*. Finally, the *h/Q* relation was developed from direct flow-measurements by means of an aDcp (Sontek River surveyor M9®) during both floods and baseflows in SIU d/s. To complete the *Q* series at ESE d/s and SIU d/s, the data measured was combined with data provided by both the CHE (in the case of the Barasona Reservoir) and the ACA (in the case of the Siurana Reservoir) from dam releases.

3.2.2. Flow hydraulics

Velocities and water depths were obtained from hydraulic simulations using the Guad-2D software (InclamSoft). Guad-2D is a finite volume based two-dimensional model for the numerical simulation of transient flows over irregular topography, under the shallow water equations hypothesis (more details in Murillo et al., 2008). Besides the DEM used for the geometrical parameterization of the model, a Manning roughness shape was defined as input according to the Cowan (1956) estimation procedure. Grain size and vegetation features were both considered. The upstream boundary conditions corresponded to a flat hydrograph for each simulated discharge, whereas downstream a critical flow regime was adopted. Results demonstrated that the lowermost downstream section of each studied reach was far enough from the model reach that this was affected by this boundary condition. A dry startup was established as initial condition for the simulations (i.e. velocity and water depth equal to zero). The simulation time was enough to obtain the steady state along the studied reach where each simulation was completed. Each simulation was calibrated by comparing the estimated wetted area against the values observed during recorded flood episodes. Results show that the model reproduces with good agreement data provided for the calibration (López-Tarazón et al., 2014). In addition, a sensitivity analysis was carried out to identify the effect of Manning's coefficient uncertainty on results. In this case, the Manning's roughness coefficients were modified in the range ±10% with respect to the calibrated ones. Changes in the water extent and flow velocities are negligible in comparison to these variations; thus model results are robust against the main hydraulic parameters. Once the model was validated, simulations for flows of interest were performed for each reach (Table 1). Raster outputs for water depth and velocity were finally obtained and used to calculate further variables as explained below.

Table 1.
Simulated Q in the study sites of the rivers Ésera and Siurana.

	Q ($m^3 s^{-1}$)											
ESE u/s	5.5	19.7	100	194.8	235[1]	400	500	600	700	800	900	1000
ESE d/s	0.3	5	50	75	100	200[2]	300	411	--	--	--	--
SIU u/s	0.05	0.1	0.29	0.6	5	10	25	50	100	200	350	471.4
SIU d/s	--	0.1	--	0.6	5	10	25[3]	50	100	200	350	471.4[4]

[1] Peak *Q* observed on October 2012.
[2] Bottom outlet maximum *Q* Barasona Dam.
[3] Bottom outlet maximum *Q* Siurana Dam.
[4] Total capacity of spillway Siurana dam.

Flow intensity was assessed by means of the specific stream power (ω), after Parker (2011) and Eaton and Church (2011); these authors found that ω is the variable most closely correlated with the bedload transport rate (i.e. the volume of sediment that is transported with time). ω represents the amount of work per unit time that a river may do per unit bed area (W m^{-2}) and it was estimated using Bagnold's (1966) equation [2]:

[2] $$\omega = \rho g d v S$$

Where ρ is the density of water (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), d denotes flow depth (m), v is the flow velocity (m s^{-1}) and S is the longitudinal slope (m m^{-1}).

Stream power was determined from the simulated flows (Table 1) on each site. Note that water d and v were directly obtained from hydraulic model outputs. A linear relationship between all the different modelled Q and ω was established in order to estimate the ω associated to all registered discharges. Furthermore, in order to correlate the net topographic change and the efficiency of the stream, the *total excess of stream power* (ω_e; Hassan and Zimmermann, 2012) was assessed for the period comprised between topographical surveys. First, the excess of stream power (i.e. ω-ω_0) was calculated for every recorded discharge (i.e. 15-min interval). In this case, ω_0 represents the stream power at the threshold of motion of bed-material (i.e. considered as the D_{50} of the surface material, of each site in this study; as per Bagnold, 1980; Hassan and Church, 1992a). In our case, ω_0 was estimated from the established relationship between peak discharge and the corresponding mobilized maximum particle size for each site (Fig. 4; see section 3.4 and Lobera et al., 2016 for more details on the mobility study). Secondly, all the individual results of ω-ω_0, calculated every 15-min for the periods comprised between topographical surveys, were accumulated to obtain the ω_e. As it encompasses all flows with the capacity to move at least the D_{50}, it is a measure of the effective hydraulic motion and includes the magnitude and the duration of each event (Hassan and Zimmermann, 2012).

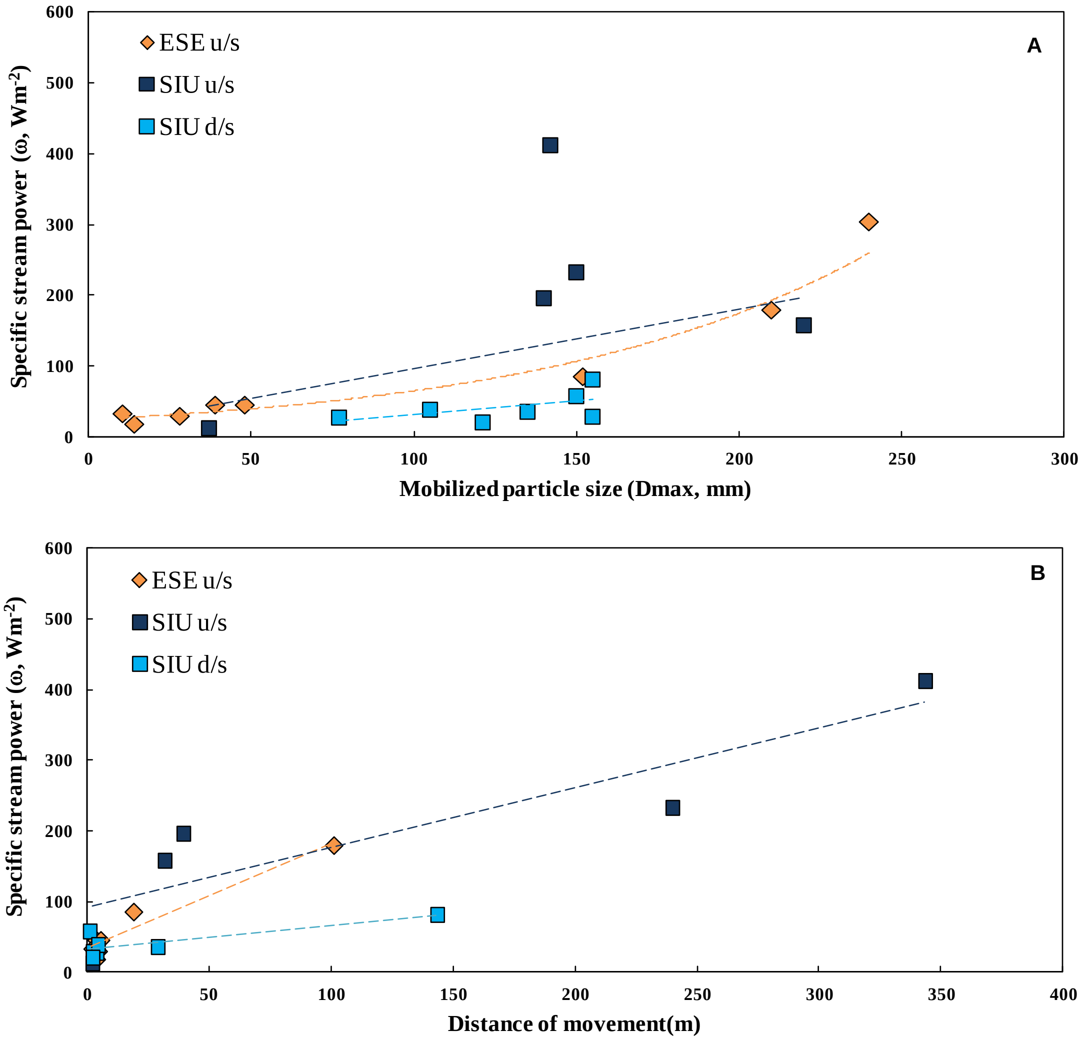

Figure 4. *(A) Relations between specific stream power and the largest particle size (D_{max}) mobilized in each flood event in ESE u/s, and SIU u/s and SIU d/s. Note that no data is available for ESE d/s. (B) Relations linking the specific stream power and the maximum distance of movement (L_{max}) of the tracers in ESE u/S and SIU u/s and d/s.*

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3.3 Bed-material characterization

Surface and subsurface materials were characterized independently, at the same time when topographic surveys were undertaken. Grain size distributions (hereafter GSD) of the surface bed-materials were determined by pebble counting (Wolman, 1954). Samples were measured using a gravel template with squared holes of ½ phi unit classes following the Wentworth scale. On average, 500 pebbles were measured in each field campaign at each site. Additionally, bulk samples were obtained in the sandy patches (which were only present in SIU u/s). Subsurface material was characterized using the volume-by-weight method (Church et al., 1987) in reaches presenting exposed bars. Only one sample per site was obtained. The sampled area was typically 1 m^2, with the volume of the subsurface sample determined based on the weight of the largest particle found. On average, largest particle sizes represented less than 1% of the total sampled weight (Church et al., 1987). Subsurface materials were post-processed in the laboratory, where they were dried, sieved and weighted according to the Wentworth scale. Furthermore, close range aerial photographs were obtained by a helium balloon, georectified and mosaicked following the approach by Vericat et al. (2009) in order to map the morphological units of the reaches (examples in Fig. 1).

3.4 Bed mobility

Bed mobility was estimated using painted pebbles (either aligned or areas) and Radio Frequency Identification (RFID) tags. The use of one type or the other was selected according to the particular channel characteristics of each site (e.g. GSD, reach slope, expected mobility). Altogether, four 1×1 m painted areas were placed at different heights in the centre of a main gravel bar (i.e. 200 m in length, 25 m width and 1.5 m of maximum difference height) in ESE u/s. The same location of the areas was kept during the study period and they were always photographed before and after each flood. In turn, two 1×1 m painted areas were located in the head and middle sections of a gravel bar (i.e. 40 m in length and 10 m in width) in ESE d/s. SIU u/s did not present permanent gravel bars in the study reach but it had small mid and lateral bars formed mostly by fine particles (i.e. 8-30 mm); this allowed painting a 0.5×0.5 m area. The location of this area changed during the study period due to the high dynamism of the riverbed. In addition, two lines of painted particles (i.e. ranging from 20 to 181 mm) were placed in the channel to observe coarse sediment mobility. Finally, two painted lines (i.e. ranging from 16 to 128 mm) and 27 particles with RFID tags (e.g. Liébault et al., 2012) were placed in the channel of SIU d/s since the reach did not show any viable bar along the study area. In all cases, the painted and RFID tracer particles were positioned by means of a Leica® GNSS/GPS and a Leica® TCRP1201 Robotic Total Station (as previously explained for the surveys), before and after each flood event. The displacement distance was later calculated using the ESRI™ software ArcMap™ 9.3. A summary of the observed mobility patterns were recently reported by Lobera et al. (2016), although the objective was different; in that case mobility was used as a proxy of bed stability to link to invertebrate communities and traits.

4. RESULTS

4.1 Hydrology

The first study year (2011-12) was notably drier than the long-term average (342 hm^3 *vs* 600 hm^3 y^{-1} for the period 1949-2012) in ESE u/s, while the following year was slightly wetter (706 hm^3) than the mean. The mean annual Q was 16.5 m^3 s^{-1} for the whole study period, with a Q_{ci} of 477 m^3 s^{-1} observed on June 2013 (corresponding to a return period of 8 years, i.e. Q_8; Table 2). The second highest event was recorded on October 2012 (235 m^3 s^{-1}, Q_2) and the third largest event was measured on February 2013 (148 m^3 s^{-1}, Q_1). Another 34 flood events of lower, magnitude were also recorded (Fig. 2a), ranging from 2 to 97 m^3 s^{-1} (floods have been considered as the events in which Q exceeded 1.5 times the baseflow at the beginning of the rainfall event; as per García-Ruiz et al., 2005). In turn, the first year in ESE d/s was extremely dry (9 hm^3), as the dam gates were totally closed until January 2012. The second year was slightly more humid (126 hm^3) if compared with the long-term mean annual runoff (i.e. 69 hm^3, for the period 1991-2012). Mean annual Q was 1.9 m^3 s^{-1} with a maximum Q of 411 m^3 s^{-1} recorded in June 2013 (i.e. Q_{10}). Two more events of 70 and 75 m^3 s^{-1} were recorded in January and May 2013 (both $<Q_{1.5}$). Hydrological data indicates that, overall, Q was remarkably altered if compared with that registered upstream (Fig. 2b; Table 2), with a reduction of both the mean daily Q (from 16.5 to 1.9 m^3 s^{-1}) and the number of floods (from 37 to 3), although the magnitude of the maximum Q for the whole study period was not modified.

Table 2.
Summary of flow characteristics at the monitoring sections of the Ésera River and Siurana River during the study period 2011-2013.

	Mean flow (m^3s^{-1})		**Minimum flow (m^3s^{-1})**		**Maximum flow (m^3s^{-1})**		**Peak discharge (m^3s^{-1})**		**Number of floods**	
	u/s	d/s	u/s	d/s	u/s	d/s	u/s	d/s	u/s	d/s
Ésera (ESE)	16.5	1.9	1.18	0.3	237	290	477	411	37	4
Siurana (SIU)	0.15	0.16	0.01	0.01	8.42	3.85	33	5.87	6	13

In the Siurana, the mean annual runoff upstream from the dam (i.e. natural regime) was 3 and 8 hm^3 for the first and second years respectively, that allows classifying the first year as dry and the second as humid, in relation to the average 5.5 hm^3 for the period 1991-2013). The mean *Q* was 0.15 $m^3\ s^{-1}$. Six flood events were recorded during the study period, with peak *Q* ranging from 1.9 to 33 $m^3\ s^{-1}$ (Fig. 2c; Table 2). Floods were flashy in all cases, showing high *Q* peak and abrupt rising and falling limbs all in few hours. In turn, the mean annual runoff was almost 5 hm^3 in SIU d/s during both study years, with a mean *Q* of 0.16 $m^3\ s^{-1}$. A total of 13 events of similar magnitude were recorded (flood peak ranging from 0.4 to 5.3 $m^3\ s^{-1}$; Fig. 2d).

4.2 Topographic changes

A total of five DEMs were used to analyse the topographic changes at the unregulated sites of both catchments (Fig. 2). Only two DEMs were obtained in the regulated reaches (i.e. at the beginning and at the end of the study period, see methods). The mean error of the DEMs ($E_{DEM\text{-}i}$) ranged between 0.06 and 0.27 m. The largest values were obtained at the ESE d/s (i.e. 0.22 and 0.27 m for the DEM at the beginning and at the end of the study period respectively). These largest errors are probably attributed to the higher topographical complexity of the reach; the river were presented a large number of boulders in combination with gravels and cobbles, hence representing its topography at a 1-m grid resolution resulted in a smooth surface with less accurate results compared with individual survey observations. The combination of these errors yielded a minLoD between 0.14 and 0.35 m. Raw and thresholded DoDs were obtained for each site (Table 3). Examples of these are presented in Figs. 5 and 6 for the Ésera and Siurana, respectively. The proportion of the uncertain cells ranged between 67 and 92% (Table 3).

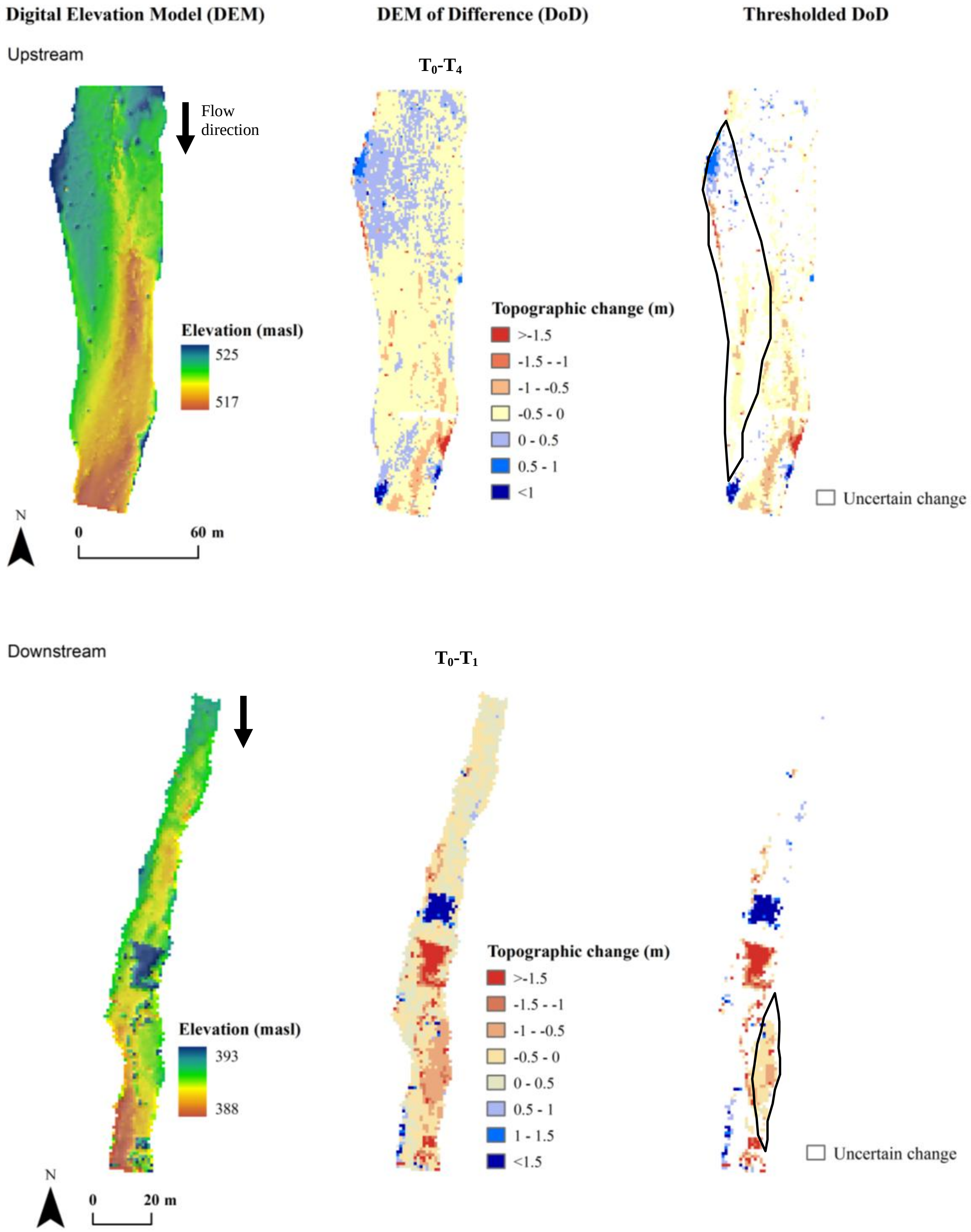

Figure 5. *Example of Digital Elvation Model (DEM) and topographic changes (DoD) in the River Ésera upstream and downstream from the dam (T_0-T_4 or T_0-T_1). Note that the thresholded DoDs were elaborated by means from minLoD (see methods). Elevation change represents deposition in blue and erosion in red. The black arrow indicates flow direction.*

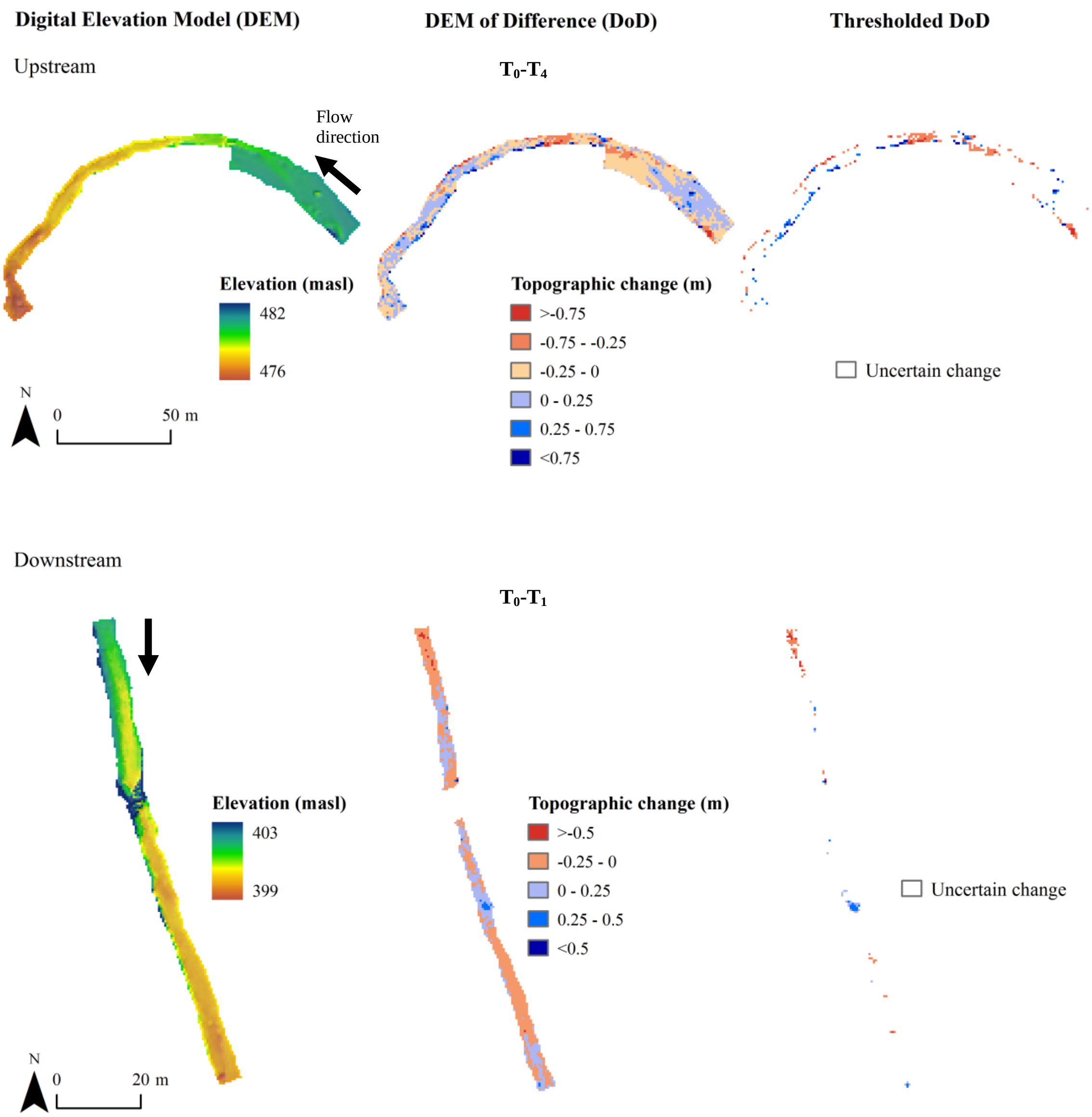

Figure 6. *Example of Digital Elevation Model (DEM) and topographic changes (DoD) in the River Siurana upstream and downstream from the dam. (T_0-T_4 or T_0-T_1). Note that the thresholded DoDs were elaborated from minLoD (see methods). Elevation change represents deposition in blue and erosion in red. The black arrow indicates the flow direction.*

Table 3.

Summary of key hydraulic variables and topographic changes (DoD results) observed between surveys (Ti) in the Ésera and Siurana monitoring sites

		Area[1] (m^2)	Q_{ci}[2] (m^3s^{-1})	Q_{ci} ω[3] (Wm^{-2})	ω_e[4] (Wm^{-2})	% uc[5]	% er_uc[6]	% dep_uc[7]	Erosion[8] (m^3)	Erosion Area[9] (m^2)	Deposition[10] (m^3)	Deposition Area[11] (m^2)	Net[12] (m^3)
ESE u/s	T_1-T_0	9070	56	83	853	89	49	40	252	544	145	400	-107
	T_2-T_1	8618	235	326	27667	84	51	33	308	1012	109	324	-200
	T_3-T_2	2982	149	180	4413	91	31	61	75	171	16	78	-59
	T_4-T_3	2982	477	654	57512	67	43	24	235	691	156	281	-79
	T_4-T_0	9070	477	654	90445	69	47	22	1119	2358	179	429	-940
ESE d/s	T_1-T_0	2147	411	1507	98724	68	38	30	590	518	424	172	-166
SIU u/s	T_1-T_0	1806	17	233	6459	77	31	46	66	173	76	244	10
	T_2-T_1	1806	33	413	NA	84	50	34	57	184	30	108	-27
	T_3-T_2	1310	11	158	10975	87	43	44	29	97	21	72	-8
	T_4-T_3	1310	14	197	19363	85	47	38	41	101	49	91	8
	T_4-T_0	1806	33	413	NA	85	46	39	86	167	63	96	-24
SIU d/s	T_1-T_0	1339	6	82	58493	92	59	33	4	59	3	45	-0.54

[1] Surveyed area
[2] Highest peak Q between the two topographic surveys
[3]Stream Power of the highest peak Q between the two topographic surveys (see methods for more details)
[4] Total Excess of Stream Power between the two topographic surveys (see methods for more details)
[5] Percentage of the total uncertain change (|elevation change| < minLoD)
[6] Percentage of erosional cells on the cells categorized as uncertain change
[7] Percentage of depositional cell on the cells categorized as uncertain change
[8] Volume of erosion (calculated using the thresholded DoD)
[9] Area of erosion (calculated using the thresholded DoD
[10] Volume of deposition (calculated using the thresholded DoD
[11] Area of deposition (calculated using the thresholded DoD[12] Net change (erosion minus deposition)

In ESE u/s, net changes ranged between -200 and -59 m^3, with the net balance always negative (i.e. erosion dominated, Table 3). It is important to take into account that the surveyed area was not exactly the same for each DoD, hence absolute values cannot be directly compared. Additionally, in some occasions several floods occurred between consecutives DEMs (see Fig. 2a), therefore this model could be subjected to local compensation of scour and fill processes that occur between surveys (e.g. Lindsay and Ashmore, 2002) that ultimately may interfere with the net balance estimates. In order to compare values between periods, thresholded volumes were also expressed in relation to the surveyed area (m^3 m^{-2}). These results were correlated with flood magnitude (Fig. 7a). The relative erosion and deposition volumes showed a significant relation at around 2:1 in all DoDs when consecutive periods are compared with the exception of the DoD for the periods T_3-T_2 (i.e. around 5:1), likely because of the low deposition values. The volumetric changes observed for the DoD corresponding to the comparison of the whole period (i.e T_4-T_0 periods) showed a very different pattern than the flood-based DoDs, with erosion up to 6 times higher than deposition. This demonstrates the importance of the temporal scale of the surveys, as it will be later discussed. In contrast, only three flood events occurred in the downstream site of the Ésera (ESE d/s; Fig. 2b). Erosion was again the dominant processes, although deposition was relatively higher than in ESE u/s. It is interesting to note contrasted scour and deposition processes i.e. on one hand, the entire sediment bar where the monitoring took place was scoured, with erosion values estimated at between 0.45 and 1 m, while, on the other, sedimentation larger than 1 m was observed in a deep pool located just upstream from that bar (Fig. 5).

In SIU u/s, the erosion volume ranged from 29 to 72 m^3, while deposition varied between 21 and 85 m^3 (Table 3). The predominance of erosion and deposition alternated during the study period; deposition prevailed between T_1-T_0 and T_4-T_3, while erosion dominated in the other two monitoring times. The net change for the entire reach was zero, indicating that erosion and deposition processes were balanced in this unmodified reach. No relation was observed between relative erosion and deposition volumes and flood magnitude (Fig. 7c). Furthermore, the area of erosion and deposition was similar between DoDs (ranging from 13 to 23%). In turn, a total of thirteen low magnitude flood events were recorded during the whole study period in SIU d/s (Fig. 2d). Here the channel did not show any significant topographic change, being erosion and deposition almost negligible (4 and 3 m^3, respectively). Similarly, the fraction of the channel that was affected by changes was low (7%).

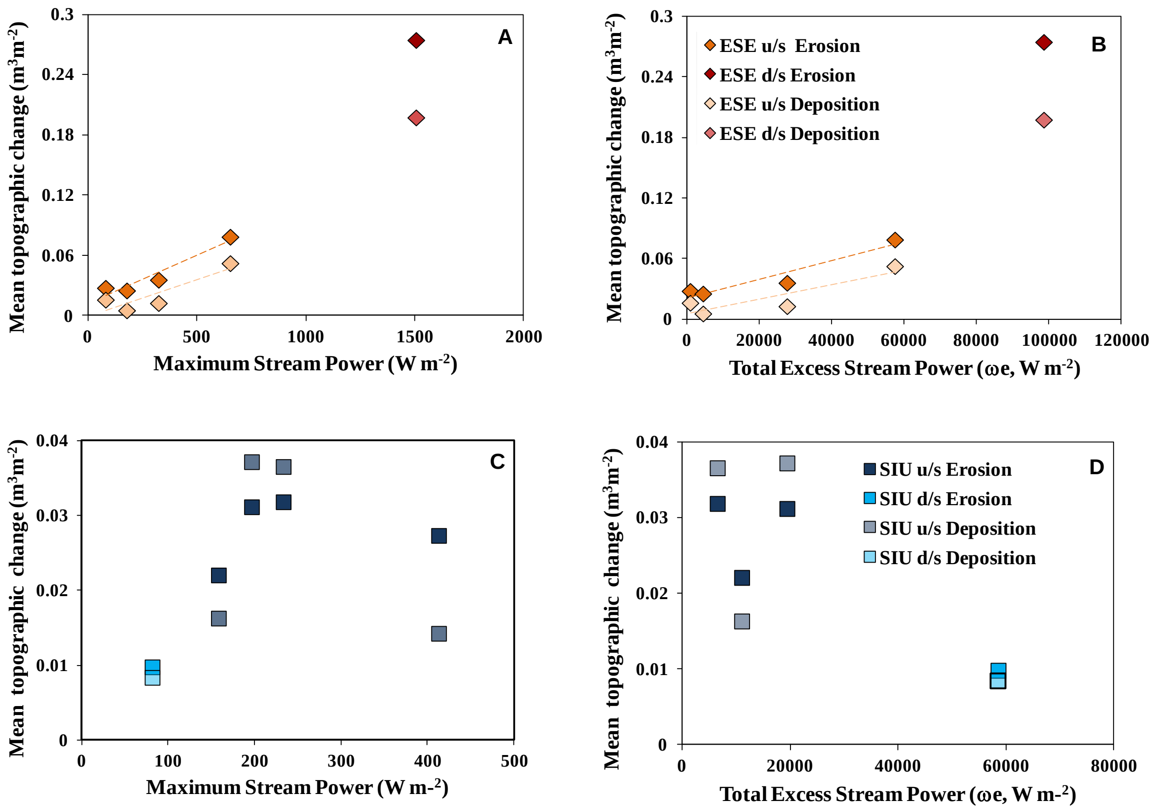

Figure 7. *Relationship between erosion, deposition and stream power in the River Ésera and River Siurana. Stream power is expressed as (A,C) the stream power associated to the maximum peak discharge (Q_{ci}, i.e. ω) between topographic surveys; and (B,D) Total Excess Stream Power (ω_e) between topographic surveys (see methods for more details).*

4.3 Changes in bed-material

Figures 8 and 9 present the GSDs at the beginning (T_0) and at the end of the sampling period (i.e. T_1 in the case of the regulated sites, T_4 for the unregulated ones, see table 3 for the characteristics of these periods). A substantial change in the GSD was apparent in ESE u/s (Fig. 8a), where surface sediment became significantly coarser (D_{50} changed from 83 to 214 mm) in the bar (statistically significant at $p<0.001$, confidence level of 95%), while the size of the sediments slightly reduced (D_{50} changed from 103 to 69 mm) in the main channel ($p= 0.12$). Additionally, the proportion of fine sediments clearly increased. The armouring ratio, calculated as the ratio between the surface and subsurface material, at T_0 was 5.18, indicating that the channel was armoured (e.g. Parker et al., 1982). The D_{50} of the surface sediments did not change at ESE d/s (i.e. D_{50} = 141 mm for T_0 and 169 mm for T_1) although the coarser fractions (D_{84}) did increase (Fig. 8b). The monitored bar was formed by relatively finer particles

(D_{50} = 83 mm), but it was completely scoured and disappeared after the largest recorded flood. The armouring ratio was 2.2, a value typically found in streams in which transport capacity exceeds sediment supply (e.g. Bunte & Abt, 2001).

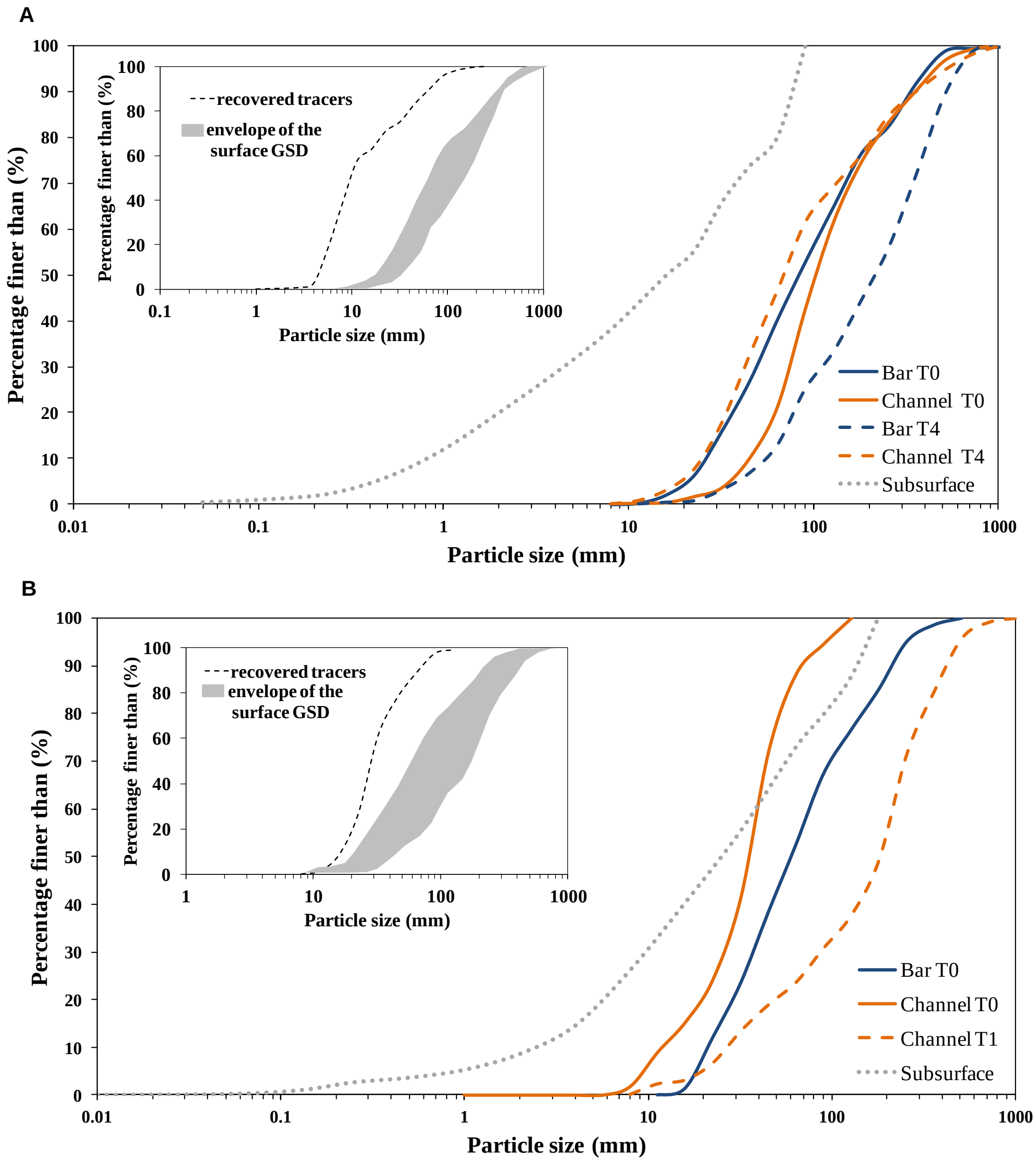

Figure 8. *Grain size distribution (GSD) at the beginning and end of the study period (T_0 and T_1 or T_4) in the (A) ESE u/s and ESE d/s study sections of the River Ésera. The inset diagram shows the envelope of the surface GSDs and the distribution of tracers.*

Three very contrasting types of sediments were observed in SIU u/s: i) fine gravels and sands that were mostly present in pools and in the plane bed (representing more than the 17% of the total active channel; D_{50} = 9 mm and D_{90} = 38 mm); ii) coarse particles that were mostly observed in riffles and bars (64% of the channel surface), presenting in both unites the same particle sizes (D_{50} = 51 mm and 53 mm, respectively, which did not change during the study period, Fig. 9a); and, iii) bedrock that occupied 19% of the channel. The surface sediment may also be finer than the subsurface sediment. The reach can be considered gravelly-sand with a mean D_{50} of the whole reach around 5.9

mm (derived from close-range images analysed by means of the Digital Gravelometer®). The armouring ratio was <1 hence the reach was not armoured, a configuration typically encountered in rivers where the supply of fine sediment covers an important part of the bed surface (e.g. Bunte and Ab, 2001). Further downstream, SIU d/s was dominated by pebbles and cobbles being the GSD very similar at T_0 and T_1 (D_{50} = 52 mm and 64 mm, respectively; Fig. 9b). Subsurface sediments were not measured here as the reach did not present any exposed area, so the armouring ratio could not been determined; however, from visual inspection, surface sediments appeared to be coarser that those in the subsurface, suggesting that the bed was likely armoured.

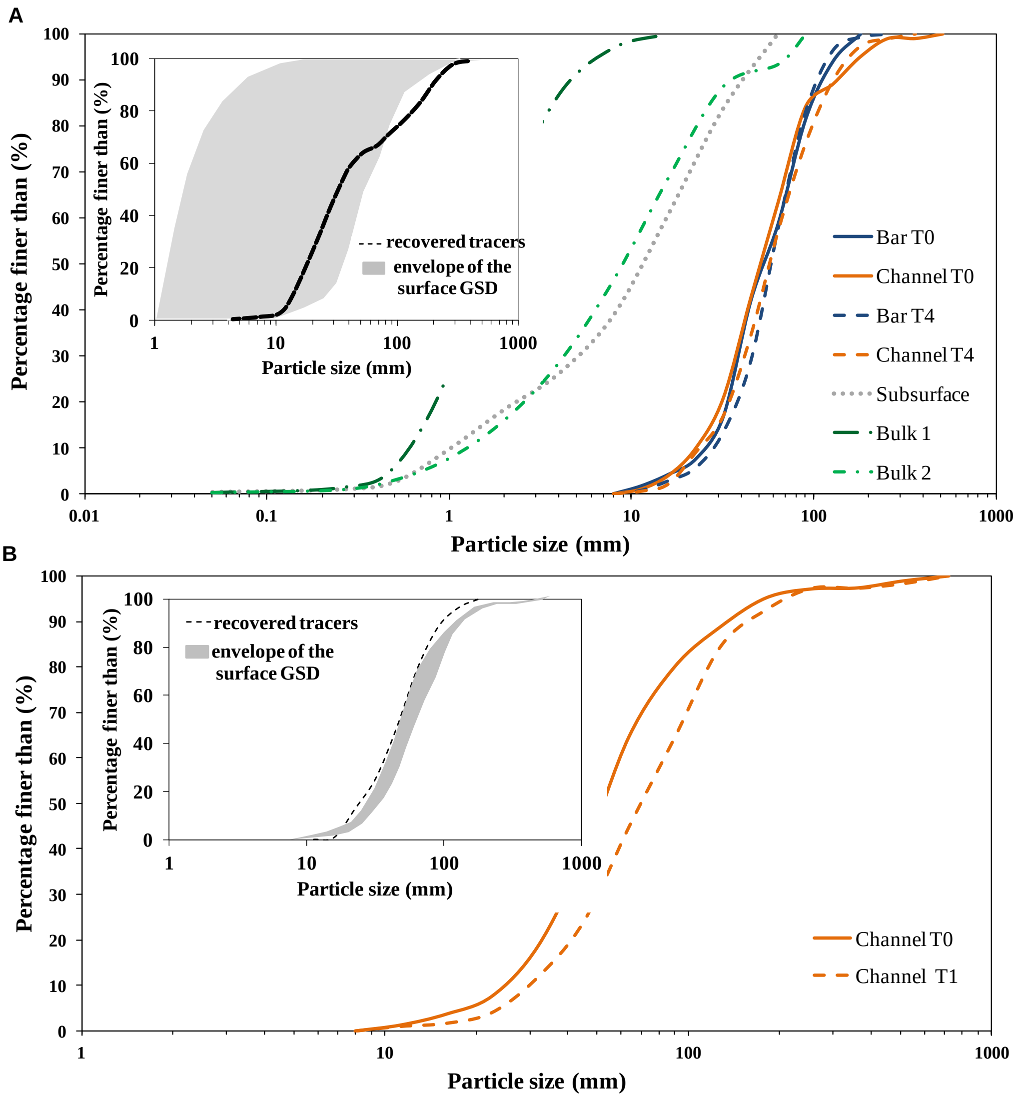

Figure 9. *Grain size distribution (GSD) at the beginning and end of the study period (T_0 and T_1 or T_4) in the (A) SIU u/s and (B) SIU d/s study sections of the River Siurana. The inset diagrams show the envelope of the surface GSD and the distribution of tracers.*

4.4 Bed mobility

Table 4 presents a summary of the flow events and associated sediment movement observed in the four study sites. In total, 416 displaced tracers were recovered in ESE u/s, encompassing 8 flood events (with flow peaks ranging from 37 to 235 m^3 s^{-1}). The GSD of the recovered tracers did not fall within the envelope of the surface sediments (Fig. 8a), as 50% of the recovered particles were finer than 11.3 mm (whereas the D_{50} of the surface sediment was around 128 mm; Fig. 8a). This is because most of the tracers were recovered after floods of a relatively low magnitude (i.e. considered as those with a flood peak < 60 m^3 s^{-1}; 69% of the recorded floods), so the particles that are moved under these flow conditions are always smaller than the bed D_{50}. Tracers were displaced between 0.5 and 100 m and the size of the largest particle mobilized was 240 mm (occurred during the largest flood event on 18/06/2013). The maximum particle sizes (D_{max}) mobilized seemed to be dependent on the magnitude of the peak Q (Fig. 4a). For instance, the D_{max} mobilized for the floods with flow peaks of 37, 45 and 56 m^3 s^{-1} corresponded with the D_{15}, D_{30} and D_{45} of the bed surface layer respectively, which may indicate that size-selective transport dominated. In turn, a total of 136 tracers were recovered in ESE d/s after the 75 m^3 s^{-1} flood event; unfortunately, no tracers were recovered after the largest flood observed during the study period (411 m^3 s^{-1}, 19/06/2013). The D_{50} of the mobilized particles was similar to that of the subsurface sediments (D_{50} = 25 mm; Fig. 8b), while the largest particle mobilized was of 145 mm. The maximum displacement observed during the study period was 36 m (for a particle of 32 mm).

A total of 133 tracers were recovered after five floods (ranging from 0.32 to 33 m^3 s^{-1}) in SIU u/s, and their entire GSD fell within the envelope of the surface sediments (Fig. 9a). The largest mobilized particle was 220 mm, whereas the longest displacement was 340 m, for a particle of 46 mm. Particle size and flood magnitude did not showed a clear pattern since, for instance, the largest particle (i.e. 220 mm, D_{99}) was not mobilized by the highest discharge (i.e. 33 m^3 s^{-1}), but during a flood three times smaller (11 $m^3 s^{-1}$ on 30/04/2013; Fig. 4a). Contrarily, step lengths (or total displacements) were significantly related to peak Q (R^2 = 0.8, $p<0.05$). Finally the GSD of the recovered tracers in SIU d/s was similar to that observed for the surface material (and similar to that observed in SIU u/s as well; Fig. 9b). In total 162 tracers were recovered after seven flood events of relatively low magnitude (i.e. Q ranging from 1.8 to 5.9 m^3 s^{-1}), with the maximum size of the mobilized particles greater than the surface D_{84} for almost all events. The longest transport distance was observed for the highest flood event (5.9 m^3 s^{-1}, 30/04/2013), with particles moving considerably (ca. 150 m, D_{50} = 68 mm).

Table 4.
Bed mobility in the study sites of the rivers Ésera and Siurana.

	Flood date	Q_{ci}[1] (m^3s^{-1})	Qci ω[2] (Wm^{-2})	ω_e[3] (Wm^{-2})	N[4]	D_{50}[5] (mm)	D_{max}[6] (mm)	L_{mean}[7] (m)	L_{max}[8] (m)
ESE u/s	06/04/2012	37	18	0	61	7.9	14	1.7	3.3
	30/04/2012	45	30	28.5	69	7.3	28	1.3	4.1
	03/06/2012	56	45	755	108	7.7	48	1.0	3.2
	20/06/2012	48	33	70	22	5	10	0.9	1.6
	03/06/2012*	56	45	824	26	20	39	1.3	5.0
	20/10/2012	235	304	24926	1	-	240	-	13
	26/10/2012	84	86	3593	24	41	152	3.6	19
	19/01/2013	150	180	7167	105	51	210	18	101
ESE d/s	20/01/2013	75	344	0	136	29	145	14	36
SIU u/s	21/10/2012	0.3	13	0	18	15	37	0.5	1.7
	25/10/2012	17	233	6459	11	61	150	117	240
	06/03/2013	33	413	NA	6	108	142	169	343
	30/04/2013	11	158	10975	11	103	220	12	31
	17/11/2013	14	197	19363	87	18	140	4.4	39
SIU d/s	15/07/2012	2.4	36	21348	49	58	135	5.1	28
	20/08/2012	1.8	28	6686	57	37	77	0.7	3.5
	05/10/2012*	1.9	29	12559	21	76	155	0.3	0.3
	25/10/2012	4.1	58	541	3	140	150	0.5	0.6
	22/11/2013	2.6	39	41	7	59	105	2.3	4
	30/04/2013	5.9	82	19391	16	68	155	67	143
	28/08/2013	1.28	21	5154	9	60	121	1.2	1.8

[1] Instantaneous peak Q
[2] Stream Power of the instantaneous peak Q (see methods)
[3] Total Excess of Stream Power (see methods)
[4] Number of the recovery tracers
[5] Median size of the recovery tracers
[6] Maximum size of the recovered tracers
[7] Mean displacement of all recovered tracers
[8] Maximum displacement of all recovered tracers
* Encompasses the last two floods

4.5 Flow competence

Stream power (ω) associated with flood magnitude has been calculated following equation 2 (Table 5). The ω associated to the flood peak (Q_{ci}) and ω_e were only correlated in ESE u/s (R^2 = 0.86, p<0.01, confidence interval of 95%). The highest event in both ESE u/s and ESE d/s resulted in a very different value of ω, being twice as large downstream as upstream. In the River Siurana, ω associated to Q_{ci} was always higher upstream in comparison to downstream, whereas ω_e was higher downstream. The comparison of the unregulated sites indicates that a *Q* peak of the order of 150 $m^3 s^{-1}$ in the River Ésera would equalled (in terms of ω) to a *Q* peak of 16 $m^3\ s^{-1}$ in the Siurana (ω = 200 W m^{-2}). During the study period, 3 flood events in ESE u/s and 4 in SIU u/s equalled or exceeded this value of 200 W m^{-2}.

Table 5.
Summary of flood-based peak flows, stream power (ω) and total excess of stream power (ω_e).

	Flood event	Q_{ci} [1] ($m^3\ s^{-1}$)	ω[2] associated to Q_{ci} (W m^{-2})	ω_e[3] (Wm^{-2})
ESE u/s	03/06/2012	56	83	115
	26/10/2012	84	120	3593
	19/01/2013	149	209	7166
	20/10/2012	235	326	24072
	18/06/2013	477	654	82436
ESE d/s	20/01/2013	75	344	0
	18/06/2013	411	1507	98724
SIU u/s	30/04/2013	10.9	158	10975
	15/11/2011	16.1	218.2	5106
	17/11/2013	14.2	197	19363
	25/10/2012	17.4	233	6459
	21/03/2012	22.5	290.7	7185
SIU d/s	20/08/2012	1.8	28	6685
	05/10/2012	1.9	29	5873
	15/07/2012	2.4	36	21348
	06/03/2013	3.1	46	10137
	30/04/2013	5.9	82	8519

1 Instantaneous peak Q
2 Stream Power of the instantaneous peak Q according to Eq. 2
3 Total Excess of Stream Power of the flood event calculated as $\sum\omega-\omega_0$ between topographic surveys when $\omega>\omega_0$ and where ω_0 represents the stream power at the threshold of motion of bed-material (i.e. considered as the median size of the surface material (see methods for more details)

4.5.1 Bed mobility

In order to find the threshold of ω that is needed for the entrainment of bed-material (i.e. ω_0), mobilized D_{max} were correlated with the corresponding ω associated to the peak of the flood (Fig. 4a). The ω_0 was used to calculate the ω_e for the period between topographical surveys (see section 3.2.3 for more explanations). This relation is exponential and statically significant in ESE u/s (R^2 = 0.94, $p<0.001$, for a confidence level of 95%). Unfortunately, it was not possible to calculate the same kind of general relationship in ESE d/s, where tracers were recovered after only one single flood. In that case, ω_0 was estimated according to the ω associated with the peak flow of that unique flood, as the D_{max} mobilized corresponds with the D_{50} of the surface layer. In SIU u/s relatively small floods were able to entrain very coarse particles (the April 2013 flood attaining 11 m^3 s^{-1} and capable of moving particles up to D_{95} of bed GSD was a clear example of this). For this reason, only the three smallest events were used to calculate these relations, which actually performed satisfactorily, despite not being statistically significant (R^2 = 0.6, p = 0.4). However, no significant relation between D_{max} and ω was found in SIU d/s (R^2 = 0.3, p = 0.2). No significant relationship between L_{max} and ω was found in ESE u/s. However, L_{max} appears to depend on ω in Siurana (SIU u/s and SIU d/s; $p<0.05$), so the floods of the highest magnitude caused the largest displacements of the tracers.

4.5.2 Relation between hydraulic variables and topographic change

The relative volumes of both erosion and deposition were positively related to the hydraulic variables ω and ω_e in ESE u/s (Fig. 7). The correlation was less significant for deposition (i.e. for relative erosion R^2 = 0.96, p< 0.05, and for deposition R^2= 0.88, p = 0.12, for a confidence level of 95%). Channel changes were larger in ESE d/s as both higher ω and ω_e occurred, and they were concentrated in a particular area of the reach (i.e. the gravel bar, see Fig. 5). In contrast in ESE u/s topographic changes were almost equally distributed along the river channel. In the Siurana, no statistically significant relationship was found between topographical changes and hydraulic variables, not in SIU u/s nor in SIU d/s (Fig. 7). Bed changes were low in both sites (less than 0.04 m^3 m^{-2}) and the largest change was not associated to the largest flood event.

5. DISCUSSION

5.1 Flow regime and floods

Total annual runoff, mean daily *Q* and the frequency of floods is reduced downstream from the Barasona Reservoir (River Ésera); however the Q_{ci} attained the same magnitude as upstream during the 2-yr study period. Overall, impoundment has thus markedly changed the hydrological regime in ESE d/s, from that of a typical humid mountainous catchment (driven by a nivo-pluvial regime), to one more closed to that observed in rivers of dry-semiarid regions, in which high magnitude but low frequency floods are the dominant processes for runoff and hence sediment delivery (Lobera et al, 2016).

In contrast, the Siurana Reservoir does not noticeably alter the mean daily *Q* and the annual runoff on the River Siurana, but it modifies flood magnitude and the seasonal flow regime. Flood events are very flashy in SIU u/s (i.e. of a higher magnitude and displaying abrupt hydrographs, usually within hours); conversely, peak floods are reduced by up to 80% in SIU d/s, whereas flood frequency has been largely increased(Fig. 2). Accordingly, the Siurana below the dam has changed from a typical Mediterranean stream to one of the type typically observed in more humid/temperate environments, with more permanent and stable flows (Lobera et al., 2016). Results obtained in this work are consistent with those obtained by other studies which described the effects of dams on downstream reaches in dry climates, especially altering the magnitude of floods in a more pronounced way than in more humid zones (e.g. Batalla et al., 2004; Lorenzo-Lacruz et al., 2012).

5.2 Bed disturbance

5.2.1. Changes on channel topography

While the River Ésera showed significant relationships between flood magnitude and total erosion or sedimentation, the River Siurana did not. During the 2-yr study period, the main process in ESE u/s was erosion (i.e. the net volume was always negative), probably as a consequence of the upstream historical reduction in sediment supply due to weirs and instream mining). Thus the Upper Ésera, as the majority of the catchments in the Pyrenees, is experiencing reduction in sediment supply due to human impacts, also including afforestation. Similar phenomena (i.e. bed incision) are reported in other rivers in mountain areas (e.g. Liébault and Piégay, 2001; Surian et al., 2009; Fuller and Basher, 2013), where gravel extraction and the increase in forest cover was associated to channel degradation based on differencing between successive DEMs and aerial photographs. It is worth noting that the erosion-deposition relation differs depending on the survey time-scale, ranging from 2:1 (for the single flood scale) to 6:1 (for the longer temporal scale, in this case two years; Table 3). Therefore, deposition may be underestimated if the selected survey time scale is longer. According to Vericat et al. (2016) and earlier reported by e.g. Ashmore and Church (1998), this mismatch can be explained by the fact that a significant proportion of the channel experienced repeated cut and fill cycles. Then, selecting an appropriate time-scale for sampling is essential for a correct assessment and interpretation of the erosion-deposition patterns. The magnitude of change in ESE d/s was higher than in ESE u/s, a fact that can be explained by i) the magnitude of the stream power of the largest flood event (ω was more than twice as high in ESE d/s than in ESE u/s; Table 3) so the water released from the dam was competent enough to erode and move very coarse sediments; and ii) the lack of sediment supply from upstream, which did not allow the natural replenishment of the eroded areas in the riverbed (i.e. *hungry water* effect as per Kondolf, 1997).

Small topographic changes were observed in SIU u/s; here, no relationship between the volumes of eroded/deposited sediment and the flood magnitude was found, despite the observed bed mobility indicated by the tracers. These differences suggest that topographic changes could be compensated, which led to small variations of the eroded and deposited volumes. This has been reported to occur also for different timescales, from the single event to a succession of a series of flood events (Ashmore and Church, 1998; Brewer and Passmore, 2002). Consequently, if bed disturbance is only assessed by comparing topographic surveys, results could be underestimated. Combining topographic changes and bed mobility provides an optimum approach to assess the magnitude and frequency of river bed disturbance. Finally, erosion and deposition values were negligible in SIU d/s during all the study period, demonstrating the *quasi-null* geomorphic activity of the reach, despite, surface bed sediments did move (although marginally) as discussed below.

5.2.2 Bed-material and flood competence

The rivers Ésera and Siurana have distinctly notably distinct GSD patterns (i.e. gravel bed and sandy-gravel bed, respectively) which, obviously, determine different sediment-mobility patterns, hence competence. In gravel-bed rivers ‘partial transport’ is a frequently observed process in the majority of frequent flood events (Church, 2002). This could explain the significant relation between particle size and flood intensity in the Ésera (Fig. 4a). Conversely, sediment tends to be mobile over a wider range of flows in sandy-gravel bed-rivers, and even the entire bed usually takes part in the sediment exchange with the flow because of the small size and low inertia of individual grains (Church, 2002). This mobility pattern is observed in SIU u/s, where even moderate flood events had enough competence to entrain large particles (i.e. particle size mobility is not hydraulically-limited), while their displacement was significantly related to flood intensity (Fig. 4b). Downstream from the Siurana Dam, that was also the main observed pattern, despite is not a sandy-gravel reach. This pattern could be related to the characteristics of the bed structure and materials. Surface bed-materials are also well sorted (i.e. present low range of sizes) and bed is armoured. Field observations suggest almost all ranges of pebbles moved on top of a stable bed. Thus, observed changes in topography were marginal even though the results from the tracers point out that the bed was disturbed to some degree during flood events.

5.2.3 Particle entrainment and bedload transport

River bed entrainment can be assessed from theoretical equations. Different approaches can be used to characterise this process given the intrinsic complexity of bed-material (e.g. Bagnold, 1977; Malmaeus and Hassan, 2002; Parker et al, 2011, between many others). Relations linking the critical specific stream power and the size of the mobilized particles have been reported, for instance, by Bagnold (1980) [3], Costa (1983) [4], and Petit et al. (2005) [5]:

[3] $\omega_0=0.0971(D_i)^{1.5}\log(1200d/D_i)$

[4] $\omega_0=0.03D_i^{1.69}$

[5] $\omega_0=0.13D_i^{1.438}$

where ω_0 is the critical unit stream power (W m^{-2}), d the water depth (m) and D_i the size of the mobilized particles (mm).

We have compared our empirical results with values estimated using these three equations based on results from the tracers. Following Jacob (2003) and Gob et al., (2003) the size of the mobilized particle introduced in the equations was the largest found in each event (D_{max}). Results from the formulae match our results in the case of ESE u/s, although the field-based critical stream power is reduced when particle size increases (Fig. 10). The difference could be associated with the high embeddedness of the channel bed, defined as the average fraction of a gravel particle's perimeter that is surrounded by sand and/or finer sediments (Salent et al., 2006). Embeddedness is a common phenomenon in the Ésera and it was visually assessed in the present work; however, a good proxy to that was carried out by López-Tarazon et al. (2011) who measured large accumulations of fine-sediment along the channel of the neighbour River Isábena (the main tributary of the Ésera). The loss of energy due to the resistance exerted by the embeddedness effect causes a considerably higher than normal ω_0 to be required to entrain surface particles. However, once the finest particles have been washed out, gravels become looser and it is much easier for the flow to entrain the, even the larger ones. In the case of the Siurana, the relationship between D_{max} and ω_0 is weak in both reaches. This is probably related with the nature of bed-materials in SIU u/s. For this reason, only the three smallest events were used for the comparison with the theoretical relations. ω_0 was related with particles of sizes between 40 and 140 mm in a similar way to that predicted by the equations, whereas results obtained for the largest mobilized particle differed markedly. Finally, no relation between competence and grain-size variables was found in SIU d/s, a fact probably related with the very low disturbance and the characteristics of the bed structure and materials found in the channel after damming (Graf, 2006; Lobera et al, 2015).

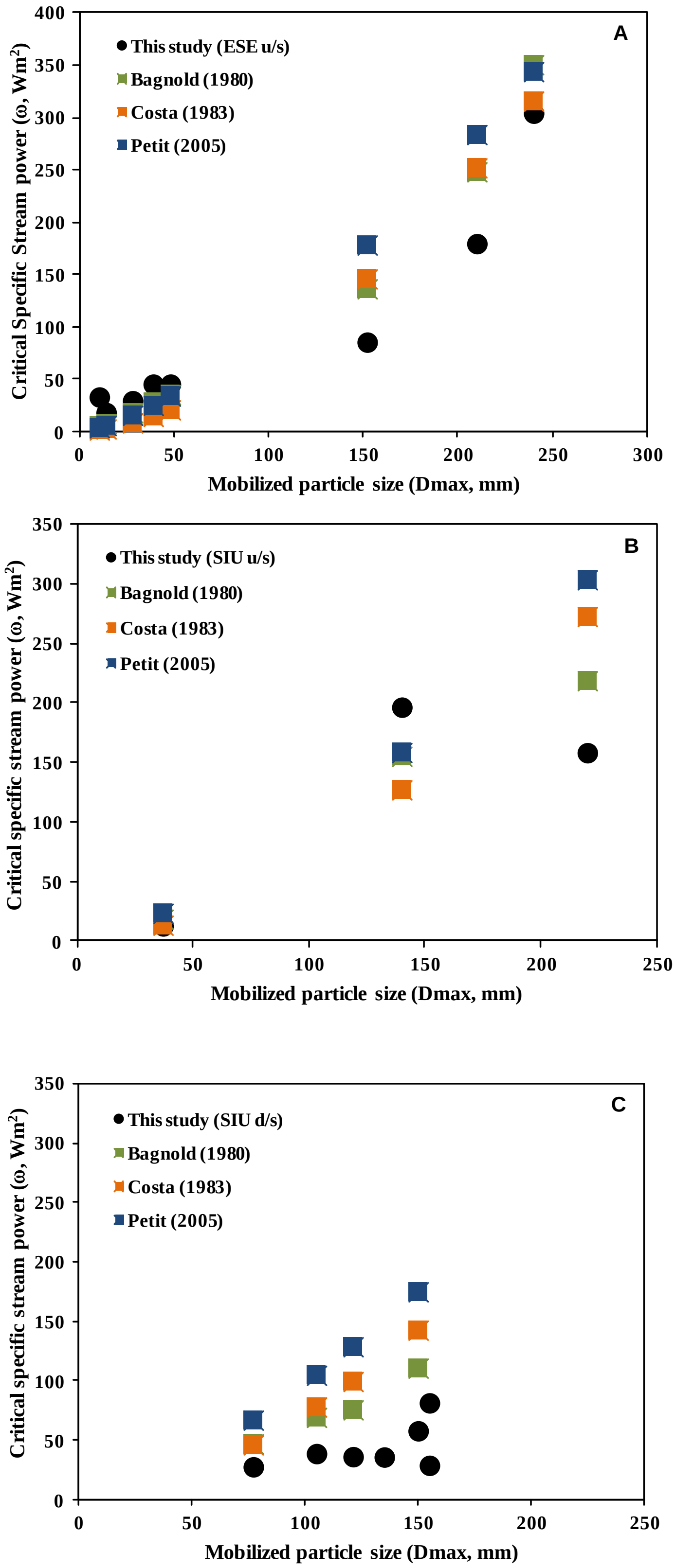

Figure 10. *Relations between the critical specific stream power and the size of the mobilized material (D_{max} in mm) in the study sites: ESE u/s (A), SIU u/s (B) and SIU d/s (C). Besides our (based on tracer data) three other relations are presented: i) Bagnold (1980),ii) Costa (1983) and iii) Petit (2005). .*

5.3 Effects of bed disturbance on ecological processes

The evaluation of the effects of bed disturbance on the biological communities and on the ecosystem processes is essential to accurately assess the relationships existing between natural and altered flows, and ecological responses (Arthington et al., 2010). Loss of natural flow variability and peak floods may lead to acute ecological effects, especially in Mediterranean streams where freshwater organisms are adapted to sequential flooding and drying periods, altogether making these fragile environments more suitable for colonisation by exotic species (Kondolf, 1997; Bonada et al., 2007a, b). The reduction of flood magnitude (i.e. flow competence) below dams creates more uniform, less dynamic habitats, reducing invertebrate diversity, shifting their assemblage from lotic to lentic species, and increasing their abundance (Petts, 1984; Allan and Castillo, 2007; Lobera et al, 2016) and the periphyton biomass (Poff et al., 1990). Such changes have been already observed in SIU d/s (Ponsatí et al., 2014; Lobera et al., 2016). It is well known that flushing flows are an important management tool to enhance the physical habitat conditions in regulated rivers, especially sections located further down from impoundment (e.g. Robinson et al., 2004; Batalla and Vericat, 2009; Tena et al., 2012). Nonetheless, Tonkin and Death (2014) reported that the effect of the water released by dams on the benthic communities was associated with substrate mobility, since a pulse flow of up to 50 times the baseflow (but still not competent enough to entrain the bed sediments) did not alter either the periphyton biomass or the macroinvertebrate communities. This phenomenon was also reported by Lobera et al. (2016) in the River Siurana, where pulses up to 50 times the baseflow below the dam are still not competent enough, with the bed seldom perturbed and never becoming fully mobile (i.e. the tracers measured after each flood only travelled short-distances). Robinson (2012) showed that larger floods are needed to produce significative macroinvertebrate drift densities and organic matter transport, in association with substantial riverbed disturbance (i.e. bed-material mobility). Morphological adjustments below the Siurana Reservoir started short after the dam was closed, so the resulting loss of channel complexity and instream habitat structure have existed for decades (Lobera et al., 2016), altogether causing significant differences in species composition of the benthic invertebrate communities and allowing higher density and biomass of invertebrates in the downstream reach.

6. CONCLUSIONS

i) Riverbeds are less dynamic below the dams. Flow and especially flood frequency and magnitude are profoundly altered in both cases; this, together with the sediment deficit associated to the presence of the dam, has created over time less active fluvial environments that, in turn, affects the instream habitat structure.

ii) ESE d/s experiences no regular disturbance, but occasionally competent floods associated to dam operations, wash out the remaining gravels in the channel and scour the remaining relict forms. These processes leave a cobbled boulder bed, which has very little geomorphic similarities with its upstream counterpart.

iii) SIU d/s has not experienced large floods for years, leaving a single thread narrow channel, where fluvial forms are not present anymore. High flows regularly released from the dam for irrigation purposes have, over time, winnowed fine particles and gravels from the bed surface. Such releases are only capable of entraining individual pebbles; the armour does not break-up and, consequently, all the spectrum of subsurface particle is virtually never entrained.

The study corroborates previous findings worldwide on the effects of dams on river channel dynamics and adds examples from an especially sensitive hydroclimatic region (the Mediterranean basin) where river geomorphology and associated ecosystems are very much dependant on the highly variable flow regimes, and resilience is lower than that commonly associated to more temperate environments. Large dams regulate natural flows and change the sedimentary regime; the unbalance between water and sediments downstream from such constructions causes profound readjustments of river forms and processes and affects the associated habitats and ecosystem functioning, precluding the success of any restoration efforts, at least in the short term.

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Chapter 6

Effects of flow regulation on river bed dynamics and invertebrate communities in a Mediterranean River

The objective of this chapter is to analyze invertebrate assemblages in relation to bed disturbance patterns upstream and downstream from Siurana dam. The chapter contains the following accepted paper and already published online:

Lobera G, Muñoz I, López-Tarazón JA, Vericat D, Batalla RJ. Effects of flow regulation on river bed dynamics and invertebrate communities in a Mediterranean River. Hydrobiologia; 784: 283-304. *Impact factor (2015):* 2.051; *Area:* Marine and Freshwater Biology; *Quartile:* 2nd.

Summary: Discharge, bed disturbance, temperature and invertebrate assemblages and functional traits are assessed in two river reaches in the Mediterranean Siurana River (upstream and downstream of the Siurana reservoir). Results show how the dam controls temperature seasonal patterns, flow and flood regimes (i.e. magnitude and frequency of floods) and, consequently, the degree of bed disturbance. Marked differences exist between the unregulated and regulated reaches. Furthermore, the results show as taxonomic composition, density and biomass of the benthic invertebrate communities were also modified by the dam.

Key Words: Channel morphology, benthic invertebrates, dams, flood regime, Mediterranean rivers, biological traits, River Siurana, Ebro catchment.

ABSTRACT

Mediterranean rivers are hotspots for biodiversity, and riverine species are adapted to regular physical perturbations that affect channel morphology during flashy rainfall-runoff events. Dams alter flow regimes, changing flood magnitude and frequency; they also interrupt the continuity of sediment transport. Changes in both flood and sediment transport regimes affect downstream channel dynamics and the ecological functioning of fluvial systems. This paper examines the effects of flow regulation on bed disturbance, invertebrate assemblages and their biological traits in a Mediterranean river (the Siurana, NE Iberian Peninsula). Results are put in the broader context of the whole Ebro river catchment. The Siurana Reservoir causes a complete inversion of the seasonal flow regime and reduces flood magnitude notably. Upstream from the reservoir, torrential floods mobilize surface and subsurface bed materials, regularly disturbing the physical habitat; downstream, geomorphological activity in the channel is almost non-existent. Altogether, damming causes significant differences in taxonomic composition of the benthic invertebrate communities: density and biomass increase notably below the dam although diversity decreases. At the broader scale taxa with active aerial dispersal traits dominate unregulated reaches in areas with marked Mediterranean hydroclimatic regimes, whereas reaches with more stable regimes are characterized by fully aquatic detritivore species.

1. INTRODUCTION

Mediterranean rivers are characterized by marked hydrological fluctuations, from low discharges (even droughts) during long dry seasons to flash floods in rainy periods on a yearly basis (McElravy et al. 1989; Molina et al. 1994; Gasith and Resh, 1999; Bonada et al., 2006). Such natural disturbances pose an evolutionary pressure that affect invertebrate assemblages and their biological traits (e.g. Bonada and Dolédec, 2011; Larsen and Ormerod, 2014). Most rivers in Mediterranean regions are heavily regulated; they host over 3,500 large dams used for water storage, hydropower production, irrigation, navigation or flood control (Cuttelod et al., 2008). Changing water demands in the future are likely to increase the need for further flow regulation. Dams alter both discharge and flood regimes and the associated downstream morpho-sedimentary dynamics. The morpho- and hydro-sedimentary responses to regulation differ greatly between rivers, depending on the location, the substrate, the amount and temporal distribution of water and, eventually, sediment supply (Brandt, 2000). Generally, reservoir effects on hydrology and river dynamics are more pronounced in drier climates (Batalla et al., 2004), since their channel form and river ecology have evolved in response to highly variable flow regimes (Gasith & Resh, 1999). Mediterranean rivers are ecologically unique with a high level of endemism (Bonada and Resh, 2013), thus the study of the effects of flow regulation on these systems are crucial to understand the functioning of these important but fragile environments and for species conservation purposes.

Moderate flood events are the main geomorphic agents in lotic habitats. When flood discharge exceeds the critical threshold to entrain river bed materials, bedload transport occurs, a process that involves the entrainment, movement and redistribution of sediments, resulting in patchy areas of scour and deposition that determine morphological changes (e.g. Schwendel et al., 2010) and displacement of biota (e.g. Lake, 2000). Regulation changes the magnitude and frequency of floods and alters the transfer of sediment downstream. These changes alter the dynamics and morphology of the fluvial ecosystems resulting, between others, in bed incision, armouring, and loss of active sedimentary areas (e.g. Vericat et al., 2006; Hassan and Zimmermann, 2012). The relationship between water and sediment transport is one of the major components of the fluvial ecosystem functioning that is fundamentally impacted by river regulation (e.g. Hauer and Lorang, 2004; Vericat et al., 2006). Reduction in peak flows typically creates more uniform and less dynamic habitats below dams, affecting macroinvertebrate diversity (especially of sensitive and native species) and increasing primary production (Petts, 1984). Reservoirs also alter the downstream water temperatures by changing both daily and seasonal patterns, thus affecting biogeochemical processes and invertebrate community structure (e.g. Petts, 1984; Jackson et al., 2007; Marzadri et al., 2013). Ecological impacts have been classically assessed by structural metrics as community diversity, although they could not differentiate the cause of the composition change or discriminate between natural and anthropogenic stressors (e.g. Buendia et al., 2013). Biological traits are more often taken as an alternative metric, independent of taxonomic constraints, which may allow determine global functional attributes of the community and their response to environmental constrains and human disturbances (e.g. Usseglio-Polatera et al., 2000; Statzner and Bêche, 2010). Recently, studies of the influence of abiotic factors on stream macroinvertebrates, in particular those related to disturbance and habitat heterogeneity, have reported significant trends in species traits, even across areas that differ in the taxonomic composition of their communities (e.g. Charvet et al., 2000; Bonada et al., 2007; Tomanova and Usseglio-Polatera, 2007; Díaz et al., 2008).

Ecological alterations in regulated rivers include reduced richness of riparian and aquatic species, increased abundance of periphyton, disrupted fish migration, and the shift of invertebrate assemblages from lotic to lentic species (Merritt and Cooper, 2000; Greathouse et al., 2006; Allan and Castillo, 2007; Tonkin and Death, 2013). However, few studies have explicitly linked substrate stability with invertebrate community structure and the prevalence of different ecological traits (but see Matthaei et al., 1999a, b). Within this context, the aim of this paper is to assess the relationships between physical and biological responses to flow regulation in the Siurana River. Specific objectives are to: i) Assess the influence of flow regulation on hydrological and thermal regimes; ii) Assess the influence of flow regulation on river bed dynamics and geomorphic conditions; iii) Assess the effects of flow regulation on the taxonomic and trait composition of the river's invertebrate communities; iv) Set the patterns observed in the Siurana within a wider, Mediterranean river context.

2. STUDY AREA

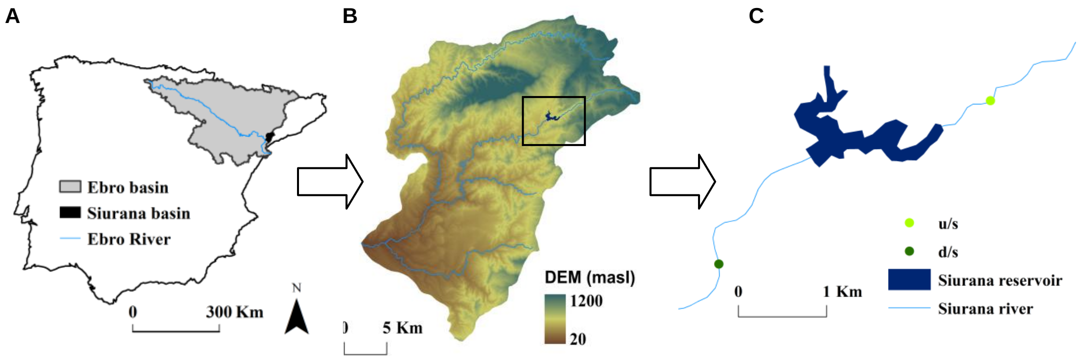

Figure 1. *(A) Location of the Siurana catchment within the Ebro Catchment and in the Iberian Peninsula. (B) Location of the study area in the Siurana catchment. (C) Location of the two study reaches located upstream (u/s) and downstream (d/s) of the Siurana Reservoir.*

The research was carried out in the River Siurana (610 km^2), which is the main tributary of the River Ebro in its lowermost part (NE Iberian Peninsula; Fig. 1). Two study reaches were selected, one located 1 km upstream from the reservoir tail and another 2 km downstream from the Siurana Dam (Fig. 1 and 2). The upper part of the catchment is mainly occupied by forests and natural vegetation (70%), while agriculture, mainly vineyards, is the predominant activity in the lowland (30% according to Corine Land Cover, 2006). The climate is Mediterranean with a mean annual precipitation of ca. 500 mm (data from 1950 to 2009; Spanish Ministry of Agriculture, Food and Environment). The Siurana Reservoir is located in the upper part of the catchment and was built in 1972 for irrigation and water supply. Its storage capacity is 12 hm^3 (i.e. 1 hm^3 = 1×10^6 m^3) a value that equates to 2.7 times the mean annual runoff of the upper catchment (i.e. 4.4 hm^3).

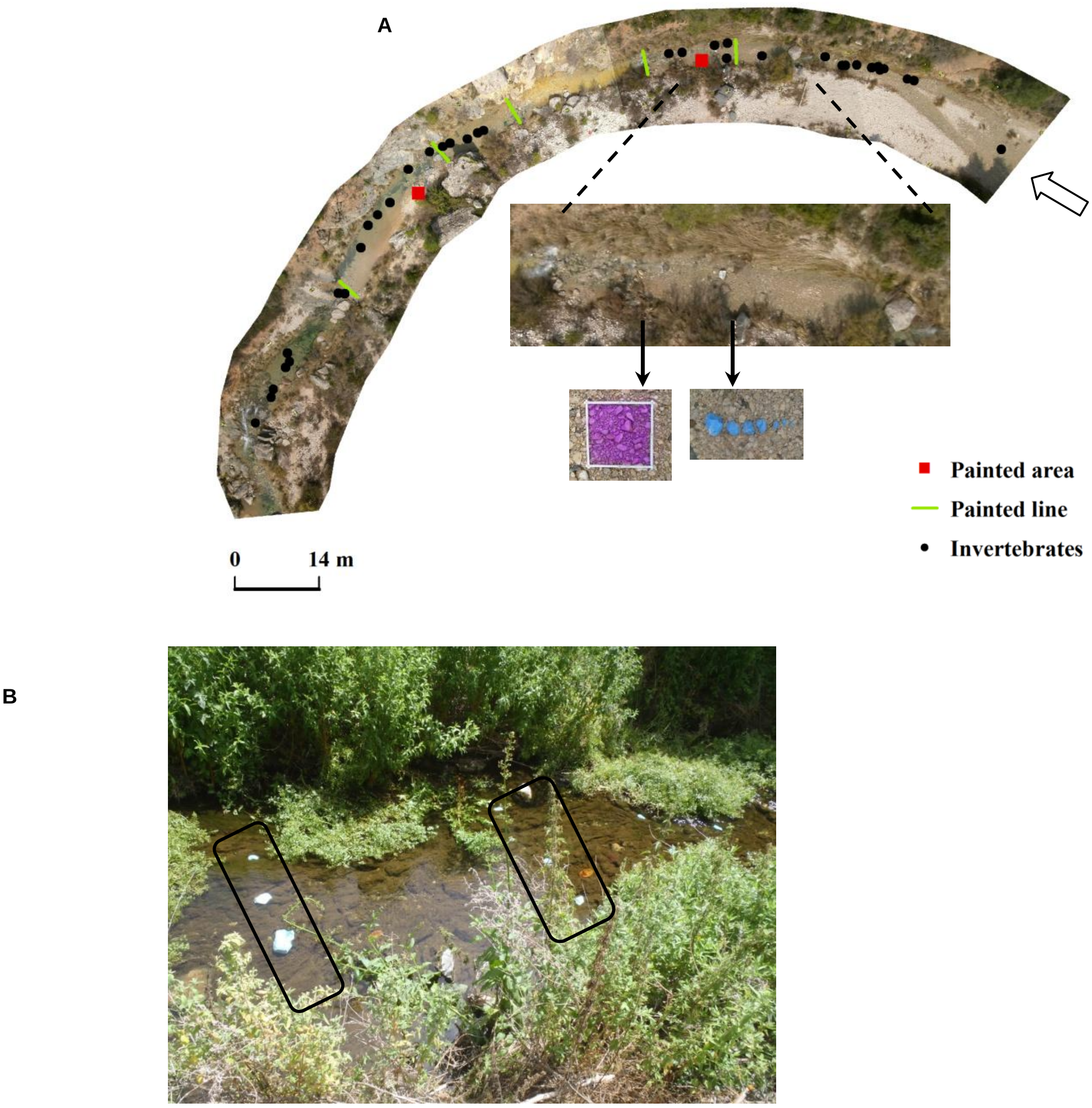

Figure 2. *(A) Aerial photograph of the upstream study reach as an example of the sampling design, showing the invertebrate sampling locations and the typology and location of the tracers. Aerial photographs were taken using a camera attached to a balloon; for more details, see the methods section. (B) Photograph of the downstream study reach, showing an example of the painted tracers.*

The Siurana has a typical rain-fed flow regime with a marked seasonality; baseflows in summer are very low and in some occasions pools in the channel remain disconnected, although the river never dries up completely (Fig. 3). In the upstream section (u/s), mean discharge (*Q*) was 0.14 m^3 s^{-1} during the study period, with a minimum of 0.02 m^3 s^{-1} in August 2012 and a maximum of 33 m^3 s^{-1} on March 2013 (which corresponded to a 4-year return period, according to data from the Spanish Centre for Hydrographic Studies –CEDEX; Table 1). Floods usually occur during spring and autumn. In the downstream section (d/s), mean *Q* was similar (0.12 m^3 s^{-1}). However, the largest peak recorded during the study period was substantially lower (5.9 m^3 s^{-1}, on April 2013; Table 1). Notable differences between flood characteristics are observed between reaches: while floods upstream can be characterised as flashy (i.e. high magnitude and very rapid rise and fall in discharge, usually within hours), high flows downstream have smaller magnitude but last longer, from days to weeks (Fig. 3a). Furthermore, seasonal variability of the river flow is altered, especially in summer, when u/s maintains marginal flows, whereas in d/s discharge is the highest of the year following water releases for irrigation purposes (Fig. 3c). Study reaches were also different in size and characteristics; the u/s reach had a length of around 200 m, a width of 8 m, and a mean slope of 0.016 m m^{-1}. It was a typical pool-riffle section, dominated by sands and gravels, being the sands mostly present in the pools and the plane bed (D_{50} = 9 mm) and the coarser particles (D_{50} = 51 mm) in the riffles. The d/s reach had a length of around 110 m, a width of 5 m and a mean slope of 0.008 m m^{-1}. It was a plane-bed river (presenting just one single hydromorphological unit) mainly composed by pebbles and cobbles (D_{50} = 52 mm). Finally, regarding water chemistry, Aristi et al. (2014) observed statistically significant but biologically irrelevant differences in water conductivity and dissolved oxygen between u/s and d/s during the study period, whereas pH and alkalinity did not change.

***Table 1**.*
Flow regime at the monitoring sections of the Siurana River during the study period 2011-2013

	Mean runoff (hm^3)	Mean Q (m^3s^{-1})	Q_{min} (m^3s^{-1})	Q_{max} (m^3s^{-1})	Q_{ci} (m^3s^{-1})	N of floods
Upstream–(u/s)	5	0.14	0.01	8.42	33	6
Downstream–(d/s)	5	0.16	0.01	3.85	5.87	13

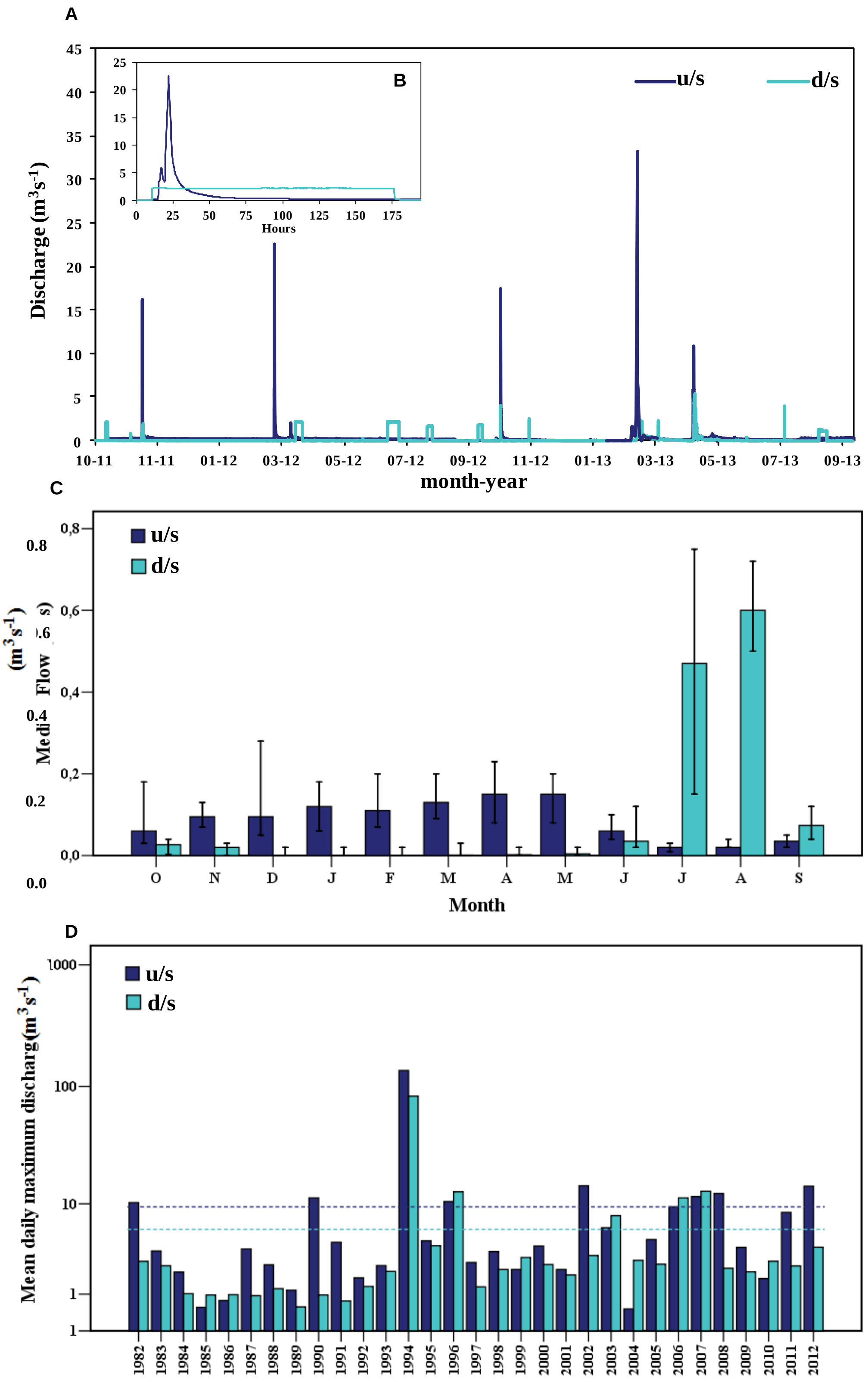

Figure 3. *(A) Discharge recorded for the 2-yr period in the River Siurana upstream and downstream the Siurana Reservoir. (B) Examples of floods recorded at both reaches u/s and d/s to illustrate the characteristically different flood patterns. (C) Median monthly discharge upstream and downstream the Siurana Dam (u/s and d/s reaches, respectively) for the period 1971-2013; whiskers show the 95% confidence interval of each monthly value. (D) Mean daily maximum discharge draining in and out of the Siurana Dam (u/s and d/s reaches, respectively for the period 1971 to 2009). Dotted line shows the average of the daily maximum discharge upstream and downstream from the dam for the whole period.*

3. METHODS

3.1. Flow and physical habitat

Flow discharge was monitored in u/s and d/s by means of capacitive water stage (*h*) sensors (TruTrack® WT-HR that also record water temperature). Discharge was derived by means of the *h/Q* rating curves specifically derived for the two study reaches based on direct gauging. The grain size distributions of the bed materials were determined by the pebble count method (Wolman, 1954). The *b*-axis of a minimum of 100 particles was measured in each of the existing mesohabitats (classified following the morphological unites described by Montgomery and Buffington, 1997). The same operator did the sediment sampling, and a minimum of two replicates were carried out in each mesohabitat during the study period. Results indicate that no statistically differences ($p<0.05$) between replicates were observed in any case. Additionally, bulk samples were obtained in the sandy reaches, only present in u/s. Representative percentiles (e.g. D_{50}, D_{90}, where D_x is the grain size for which *x* per cent of the sediment is finer) were extracted from the grain size distributions of each reach. Close range aerial photographs were obtained by a camera attached to a helium-balloon, georectified and mosaicked by means of ground control points, following the approach presented by Vericat et al. (2009). These photographs (Fig. 2) were used to map the morphological units (according to Montgomery and Buffington, 1997) of the reaches and to calculate the extension of sandy and gravel areas in u/s (in d/s sand and gravel were absent in the surface). Furthermore, two morphological indices were applied to each reach: i) the River Habitat Index (IHF; Pardo et al., 2002) and ii) the Geomorphic Status Index (GS*;* Lobera et al., 2015). The IHF evaluates the relationship between habitat heterogeneity and some physical variables of the stream channel (e.g. frequency of riffles, flow velocity, substrate diversity and aquatic vegetation), while the GS allows assessment of the degree of change of the channel geomorphic activity due to the presence of the dam. The GS index was calculated from aerial photographs obtained in 1956, 1985 and 2012.

3.2. Bed disturbance

Bed disturbance was assessed by monitoring bed mobility and topographic changes in both study reaches between competent flood events (i.e. those which are capable of entraining and transporting part of or the entire channel bed surface). The u/s reach did not present any stable gravel-bar along the whole study period, although it had small mid and lateral bars formed mostly by fine particles (i.e. 8-30 mm) that allowed painting a 0.5×0.5 m area (Fig. 2a). The location of this area was different during the study period due to changes of the channel morphology after each flood, with consequent changes on bar extension and shape. In addition, two lines of painted gravels (i.e. particles ranging from 20 to 181 mm) were located within the channel to detect coarse sediment mobility (Fig. 2a). Altogether, these tracers covered the whole range of the coarse sediment fraction present in the study reach (i.e. particle diameter from 8 to 181 mm b-axis). Two painted lines (particles ranging from 16 to 128 mm) together with 27 gravel particles equipped with passive radio-frequency identification tags (RFID tracers) were placed in d/s (the reach did not present any exposed area; Fig. 2b). The painted tracers were firstly installed in u/s on October 2012 and in d/s on June 2012. Therefore, the floods which occurred before these dates could not be monitored. Tracers were measured, at all cases, using a gravel template with squared holes of ½ phi unit classes; in both reaches the number and size of tracers was representative of the surface grain distribution of the reach. The position of painted and RFID tracer particles was surveyed by means of a Leica® GNSS/GPS and a Leica® TCRP1201 Robotic Total Station at both reaches before and after each flood event. The displacement distance of each tracer was measured using the ESRI® software ArcMap™ 9.3. Data from tracers were used to estimate the degree of bed stability by using the TTM index that expresses the magnitude of movement of the tagged sediments (Schwendel et al., 2011). All tracers recovered after each flood were classified in three classes, in which the mid-value corresponds to a characteristic percentile of the bed grain size distribution: (a) D_{50}, that includes tracers in the range $>D_{40}$ and $<D_{60}$; (b) D_{70}, with tracers between $>D_{60}$ and $<D_{80}$; and (c) D_{90} including all tracers $>D_{80}$. TTM was then calculated by applying the following equation:

$$TTM = \frac{(D_{50} \times (s_{50} \,/\, n_{50})) + (D_{70} \times (s_{70} \,/\, n_{70})) + (D_{90} \times (s_{90} \,/\, n_{90}))}{(D_{50} + D_{70} + D_{90})}$$

where s is the sum of the distance (in m) travelled by the tracers of a certain size class i between consecutive surveys, n is the number of recovered tracers of each class i, and D_i is the median value (in m) of the bed grain size distribution for that class i. High values of TTM indicate high mobility (i.e. all characteristic fractions are mobilized and displacement is relatively high). In addition, topographic changes were assessed from highly-dense surveys (i.e. the point density ranged between 0.5 and 3.5 points m^{-2}, as per Brasington et al., 2000) carried out after each competent flood event. Altogether, five surveys were conducted in u/s while two surveys (one at the beginning and one at the end of the study period) were performed in d/s, where no truly competent events were observed (i.e. mobility was minimum and very selective). Topographical surveys were carried out by means of a Leica® GNSS/GPS and a Leica® TCRP1201 Robotic Total Station; the DEM (5×5 m resolution) provided by the “Instituto Geográfico Nacional” (IGN) was used to complete the data for the terrain outside the river channel. Triangulated Irregular Networks (TINs) were elaborated from each topographic survey. TINs were converted to rasters by linear interpolation, and Digital Elevation Models (DEM) of 1 meter grid resolution were subsequently developed. DEMs were compared (i.e. DEMS of Difference, DoD) to assess the topographic changes between periods. DoDs were used to characterize the magnitude, direction and distribution of changes in both channel reaches. Erosional and depositional areas were obtained from DoDs, together with estimates of net change.

3.3. Macroinvertebrates

Macroinvertebrate communities were sampled once per reach in spring 2012. Samples were distributed according to the type and proportion of substrate previously characterized (except for bedrock that was not colonized by invertebrates) and including the flow velocity (together forming the physical habitat). A total of three habitats were defined in u/s: (i) sand and gravels and low velocity; (ii) coarse cobbles and low velocity; and (iii) coarse cobbles and high velocity. Two habitats were identified in d/s: (i) pebbles and cobbles with low velocities and (ii) pebbles and cobbles with high velocities. A total of 57 samples (37 u/s; 20 d/s) were collected and between 6 and 18 replicates were obtained randomly in each habitat in order to reduce effects of small-scale habitat variability and to arrive to the maximum number of species (species accumulation curves). Invertebrates were collected using a Surber sampler (300 µm of mesh size; 0.09 m^2 of area) and preserved with 70% ethanol. Invertebrate biomass was estimated by a length/dry mass conversion, i.e. the body length or head capsule of each individual was measured and latter related to a dry mass (mg) applying a regression function according to each specific taxon (after Meyer, 1989; Burgherr and Meyer, 1997).

Seven biological traits were used to examine the effect of regulation on invertebrate assemblages (as per Tachet et al., 2002). Selected traits reflected taxa life history (i.e. life cycle duration, dissemination), physiology (i.e. feeding habitats), habitat preferences (i.e. temperature, microhabitat, flow preferences) and mobility (i.e. locomotion and relationship with substrate). The main trait profile was obtained by weighting the individual trait profiles of each taxa by their logarithmic (x+1) abundance in the sample. Then, the sum of the weighted affinity scores of all the taxa of the reach (for each trait category) was calculated; finally, each sum of weighted affinity scores was expressed as a frequency per trait (e.g. Usseglio-Polatera et al., 2000; Descloux et al., 2014). A single factor ANOVA analysis was applied for macroinvertebrate descriptors to test whether differences between u/s and d/s samples were statistically significant. Data were log transformed to meet normality when needed. Statistical analyses were performed with the IBM SPSS® statistical software.

3.4. Regional analysis

Results from the River Siurana were compared with data from 26 reaches in the Ebro catchment with the objective of analysing the patterns in a wider hydroclimatic context. Data were obtained from the Ebro Water Authorities and contain information from 15 non regulated and 11 regulated reaches. All reaches belong to the same ecological region of the Siurana (i.e. *mineralized* low mountain Mediterranean rivers, following the classification proposed by the Spanish Centre for Hydrographic Studies -CEDEX and according to the EU Water Framework Directive 2000/60/CE). The invertebrate sampling was qualitative (kick sampling) following the protocol described by Alba-Tercedor (1996) and Barbour et al. (1999). However, despite the sampling procedure is different to that used in the Siurana, differences derived from that are not important as the two datasets are not going to be compared. Data at each reach were composed of relative invertebrate abundance and mean daily *Q*. All reaches were categorized as having good ecological status after the *IBMWP* index (Alba-Tercedor et al., 2002) to ensure that no other perturbations different from regulation exist. Additionally, two more variables were calculated to assess the degree of Mediterraneity of the reaches: i) torrentiality, which expresses the relative magnitude of the floods, represented by the ratio between the median of the peak *Q* of the series (i.e. annual instantaneous maximum, Q_{ci}) and the median annual *Q*; and ii) seasonality, considered as the ratio between the mean daily *Q* of the two most contrasting seasons (i.e. summer and spring). In addition, the drainage catchment area, the mean annual daily *Q* and the Impoundment Ratio (*IR*; Batalla et al., 2004) were also calculated. Ten years of data records were used to calculate all these hydrological variables. First, a detrended correspondence analysis (DCA) of the arcsin square-root-transformed relative abundance data was performed. The gradient length from the DCA was 2.24, indicating that the linear method (Redundancy Detrended Analysis, RDA) was more appropriate to understand the relationships between hydrological parameters and invertebrate assemblages (ter Braak and Smilauer, 2002). Finally, a Pearson correlation matrix was applied between macroinvertebrate data and hydrological parameters. Data were analysed using the statistical software CANOCO® 4.5 and StatSoft STATISTICA® 7.0.

4. RESULTS

The mean annual runoff (i.e. 5 hm^3 at both reaches) and the mean daily *Q* (i.e. 0.14 $m^3 s^{-1}$ at u/s and 0.16 $m^3 s^{-1}$ at d/s) upstream and downstream from the reservoir were very similar during the study period (Table 1). However, the seasonal flow regime was inverted downstream: while a low *Q* (i.e. 0.09 $m^3 s^{-1}$) was flowing in summer upstream, a *Q* higher than the mean (0.22 $m^3 s^{-1}$) was flowing downstream (Fig. 3c). Furthermore, the dam also modified the flashy character of the floods in u/s: their maximum *Q* was reduced by up to 80% downstream but they were longer-lasting, increasing in duration from a few days to several weeks (Fig. 3a). The thermal regime between reaches also differs greatly. Temperature in u/s was more variable during the year and the maximum and minimum were more extreme than in d/s (Fig. 4b). Mean daily temperatures were higher upstream (between April and October), and especially in periods of flow releases from the dam (i.e. up to 15ºC of difference in July). In contrast, temperature was constantly warmer in d/s from November to February (Fig. 4a).

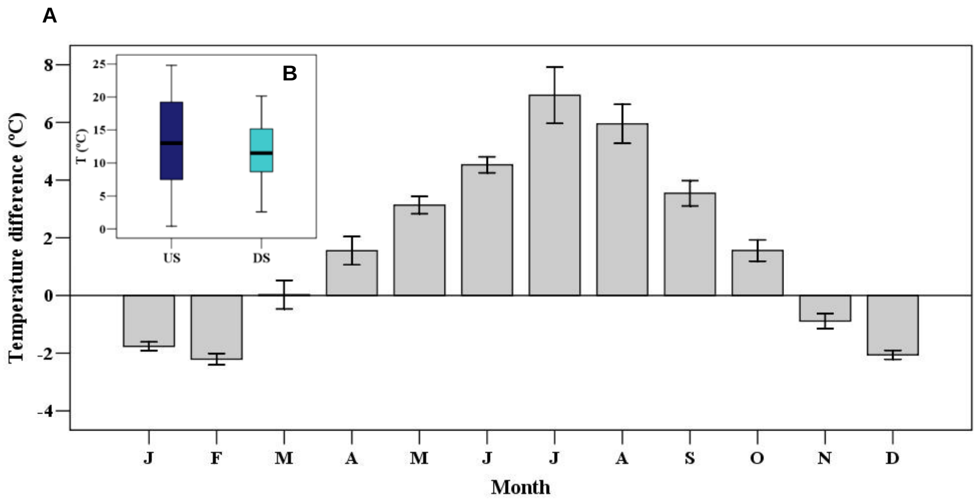

Figure 4. *(A) Differences in water temperature between the study reaches (u/s and d/s). Bars represent the median of the temperature u/s minus the temperature d/s; whiskers represent the 95% confidence interval of each monthly value. Positive values indicate colder temperatures in u/s than in d/s. The inset represent: (B) Box plot of the mean daily temperature during a regular year at both sites. Plot contains the median values (central line of each box), the quantiles 25 and 75 (upper and lower side of the box) together with the non-outlier range (whiskers).*

4.1. River morphology and habitat

Changes in river morphology are evident downstream from the dam. The Geomorphic Status index (GS) in d/s in 1985 was already 1.4 (Fig. 5), indicating a remarkable low geomorphic activity, 13 years after dam closure. Particularly, the study reach showed a large reduction in both the active channel width (i.e. from 28 m to 7 m) and the number of sedimentary structures (i.e. from 12 bars per km to none). As the channel was already totally degraded in 1985, GS was again 1.4 in 2012. In turn, GS in u/s could not be fully estimated since the river runs through a narrow valley compared to the resolution of the aerial images. However a comparison by eye of the historical and modern aerial photos indicates that no appreciable change has taken place (i.e. the mean width of the active channel has kept constant and at around 10 m during the period 1956-2012), so the river upstream from the dam displays a natural active behaviour.

Three different environments were observed at u/s: i) reaches that were mainly composed by sand and fine gravels (<16 mm), mostly present in pools and plane bed (i.e. more than the 17% of the total active channel surface; D_{50} = 9 mm and D_{90} = 38 mm); ii) coarser areas that correspond mostly to riffles (64% of the channel surface; D_{50} = 51 mm and D_{90} = 134 mm); and iii) bedrock that occupies 19% of the channel area. In contrast, d/s was composed of one type of habitat (pebble-cobble sized sediment; D_{50} = 52 mm and D_{90} = 135 mm) forming a plane bed morphology. The River Habitat Index (IHF*)* shows a structural simplification at both reaches: it scored 53 out of 100 points in u/s and 52 in d/s. Although the final score is similar, the upstream reach obtained a higher score for habitat heterogeneity (i.e. riffle/pool) and diversity of substrates, but lower values for aquatic vegetation coverage and heterogeneity elements (e.g. leaves, branches, shaded areas).

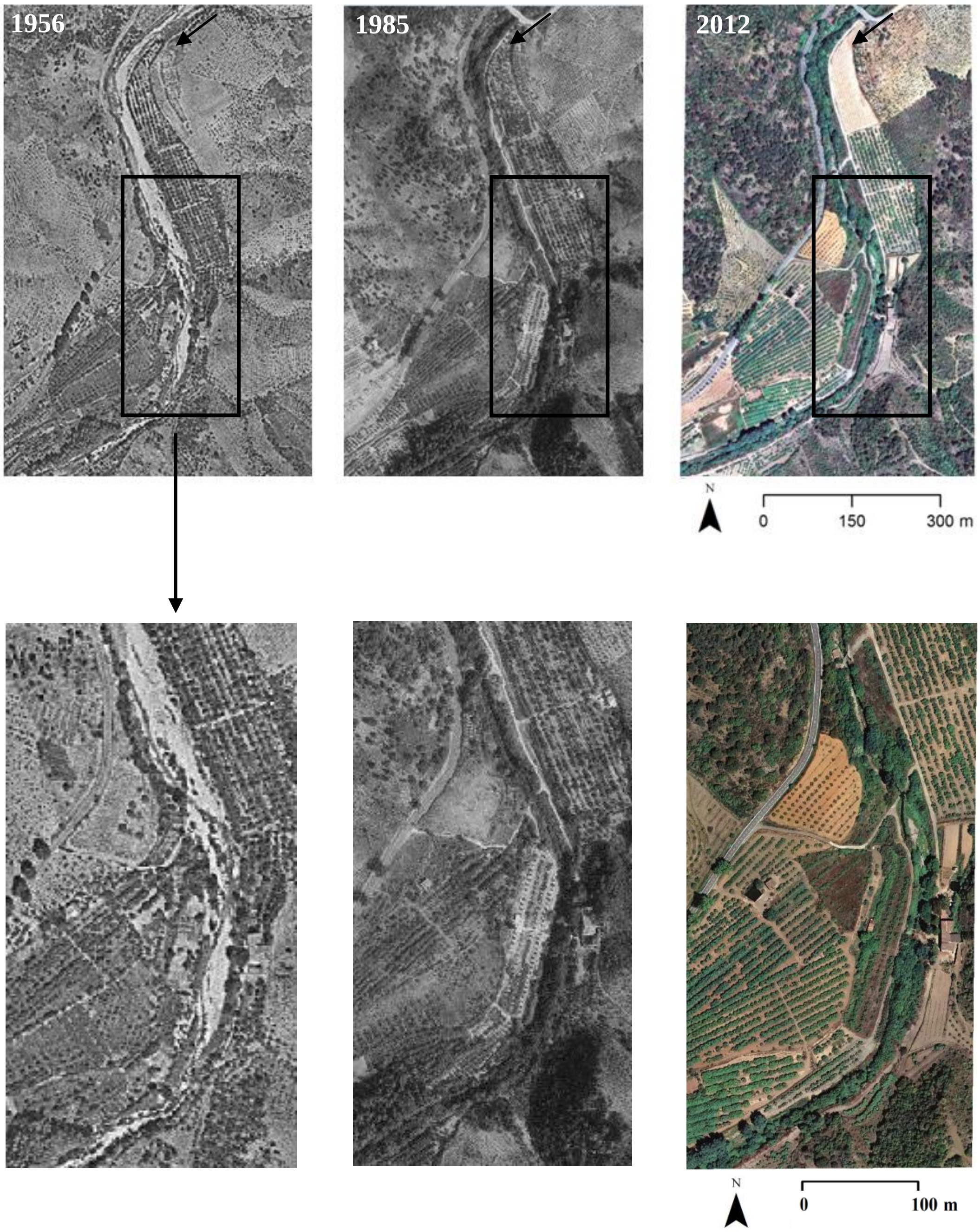

Figure 5. *Historical aerial photographs of the downstream reach to show the evolution of the reach after the Siurana Dam construction. Note that the rectangle indicates the area that is presented in detail in the bottom photographs. Left to right: image of 1956, 1985 and 2012 (source: Spanish National Geographical Institute –IGN).*

4.2. Bed disturbance

Six flood events were recorded in the u/s section (Fig. 3a), with five of them monitored for particle mobility and morphological changes. The largest event was recorded on the 6 March 2013 with a peak Q of 33 $m^3 s^{-1}$ (that corresponds to 4-yr recurrence interval; #F2); other floods were of appreciable lower magnitude (#F1: 17 $m^3 s^{-1}$; #F3: 14 $m^3 s^{-1}$; #F4: 10 $m^3 s^{-1}$ and #F5: 0.3 $m^3 s^{-1}$). In total 133 tracers were found during the recovering surveys within the study period (Table 2); the size (*b*-axis) of the largest particle mobilized during a single flood was 220 mm, whereas the longest step length was 340 m (for a particle of 46 mm that represents the D_{40} of the surface material).

Table 2.
Summary of the recovered tracers data, including the magnitude of the highest flood events between surveys

	Flood date	Qci[1] ($m^3 s^{-1}$)	N[2]	D_{50}[3] (mm)	D_{max}[4] (mm)	L_{mean}[5] (m)	L_{max}[6] (m)
Upstream–	21/10/2012	0.3	18	15	37	0.5	1.7
(u/s)	25/10/2012	17	11	61	150	117	240
	06/03/2013	33	6	108	142	169	343
	30/04/2013	11	11	103	220	12	31
	17/11/2013	14	87	18	140	4.4	39
Downstream–	15/07/2012	2.4	49	58	135	5.1	28
(d/s)	20/08/2012	1.8	57	37	77	0.7	3.5
	05/10/2012*	1.9	21	76	155	0.3	0.3
	25/10/2012	4.1	3	140	150	0.5	0.6
	22/11/2013	2.6	7	59	105	2.3	4
	30/04/2013	5.9	16	68	155	67	143
	28/08/2013	1.28	9	60	121	1.2	1.8

[1] *Instantaneous peak discharge*
[2] *Number of the recovery tracers*
[3] *Median size of the recovery tracers*
[4] *Maximum size*
[5] *Mean displacement*
[6] *Maximum displacement*
* *Encompass the last two floods*

The recovery ratio value could be considered as low; however, it is well known that sediments use to be mobile over a wide range of flows in sandy-gravel bed channels (i.e. u/s section), and even the entire bed usually takes part in the sediment exchange with the flow because of the small size and low inertia of individual grains (Church, 2002). Hence after flood events, the majority of the recovered tracers use to belong to the coarsest fractions of the grain-size distribution of the channel (only a reduced fraction of fine particles is found). This way, most of the tracers recovered were larger than the D_{50} (51 mm) of the grain-size distribution of the coarser areas in the channel (habitat n.2, see previous paragraph for details). Owing to its smaller magnitude, #F5 was only competent enough to entrain and transport a restricted range of sizes, corresponding to the D_{90} (38 mm) of the fine component of the surface material (i.e. fine gravel and sand that represented ca. 17% of the total area of the study reach). The maximum particle size (D_{max}) mobilized per flow event not depend just on flood magnitude. As figure 6a shows, moderate floods had enough competence to disturb substantially the surface layer of the bed and transport virtually all particle sizes. The TTM index ranged between 0 (i.e. no displacement) to 169 (i.e. the largest disturbance episode during #F2). In the particular case of low and moderate floods with enough competence to entrain large fractions, the magnitude of the TTM (i.e. that is taken as a proxy to characterize the magnitude of the disturbance) was directly related to flow intensity (Fig. 6b). Finally, DoDs showed that channel topography changed during floods (Fig. 7). Channel erosion and deposition processes were observed after each event (Table 3) although values were rather low (in the range of the median particle size).

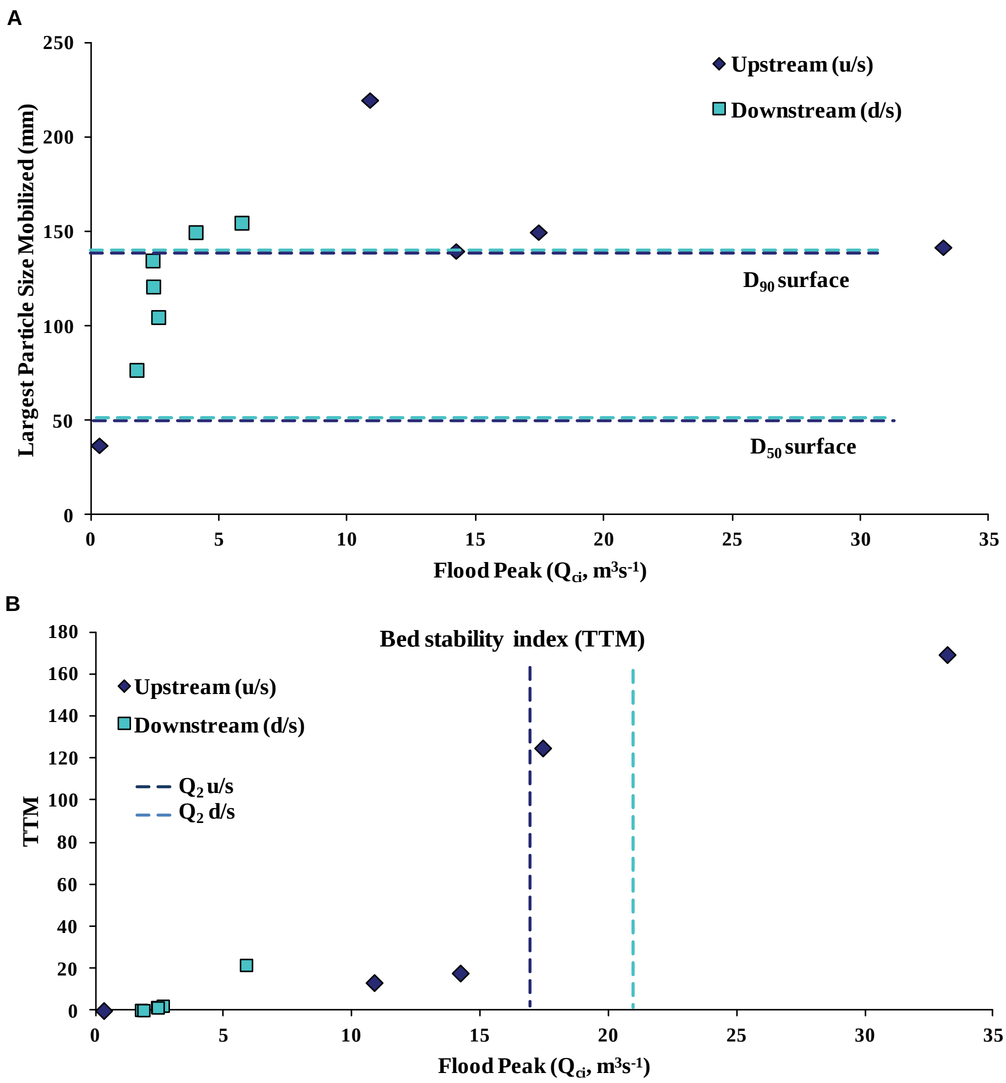

Figure 6. *Relations between the flood instantaneous maximum discharge (i.e. Q_{ci}) and the maximum size of the particles mobilized (D_{max}) by each flood in the upstream - u/s and the downstream - d/s reaches. (b) Relations between the flood instantaneous maximum discharge (i.e. Q_{ci}) and the bed stability index TTM (after Schwendel et al., 2011) for u/s and d/s. Dotted lines in a) indicate the D_{50} and the D_{90} of the surface bed, whereas in b) dotted lines indicate the discharge corresponding to the 2-yr return period u/s (dark blue) and d/s (light blue).*

In d/s 13 flood events of relatively similar magnitude (*Q* peak ranging from 1.2 to 5.9 $m^3 s^{-1}$) were recorded during the study period (Fig. 3a). The maximum registered *Q* peak represents less than 20% of the maximum peak in the u/s section. Seven flood events were monitored for particle mobility (Table 2). In total, 162 tracers were recovered, 150 mm being the size of the largest mobilized particle (corresponding to the D_{92} of the river bed). The longest step length was 143 m (for a particle of 59 mm). All floods were capable of entraining particles larger than 60 mm (corresponding to the D_{60} of the bed, Fig. 6a). Mobility was hydraulically driven, as the size of the largest recovered tracers increased with peak flood. The largest travel distances were observed for the highest recorded flood (5.9 $m^3 s^{-1}$). Although these mobility patterns were evident, the TTM index was very low (near to 0) due mainly to the short travel distance. The largest TTM in d/s was around 20; nine times lower than the maximum value obtained in u/s. These differences indicate the different disturbance regime in both reaches. Regarding the topographical changes on the river bed, erosion and deposition values were negligible during the whole study period, pointing to the low geomorphic activity of the reach with just some scattered particles moving along the armoured riverbed (Fig. 7; Table 3).

Table 3.

Summary of results obtained after comparing consecutives DEMs in the River Siurana, illustrating the erosion (i.e. material loss), deposition (i.e. material gain) and net (i.e. difference between deposition and erosion) changes. The mean linear erosion and deposition, together with the percentage of the area eroded and deposited are also shown. For reference, the highest instantaneous discharge (Q_{ci}) which took place between the two topographic surveys is also included.

	Q_{ci} ($m^3 s^{-1}$)	Erosion volume (m^3)	Mean erosion (m)	Erosion area (%)	Deposition volume (m^3)	Mean deposition (m)	Deposition area (%)	Net change (m^3)
Upstream –	17	66	0.4	8	76	0.3	11	10
(u/s)	33	57	0.3	9	30	0.3	5	-27
	11	29	0.3	7	21	0.3	5	-8
	14	41	0.5	7	49	0.6	7	8
Downstream	6	4	0.2	7	3	0.2	4	-0.5
(d/s)								

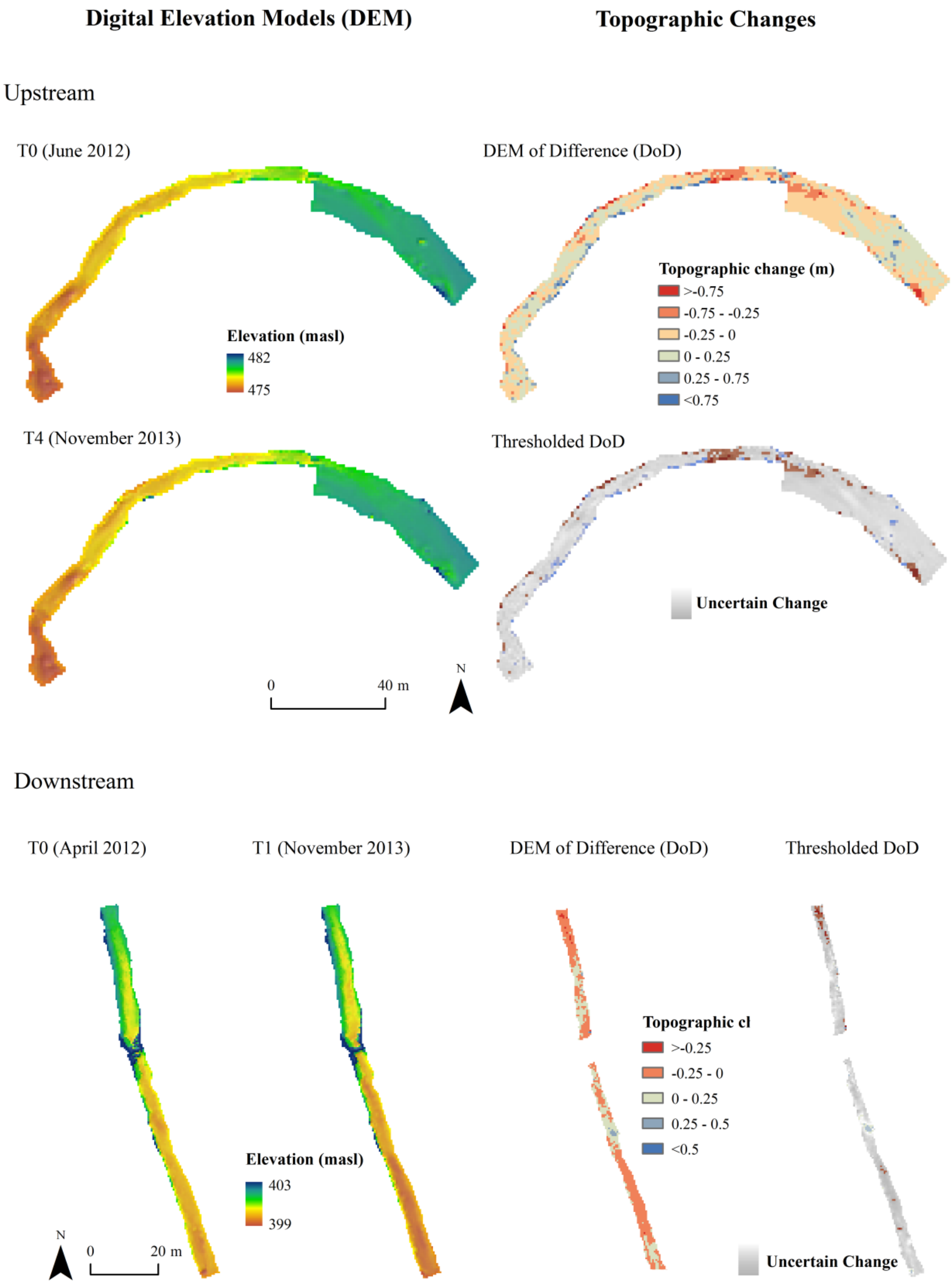

Figure 7. *Example of Digital Elvation Model (DEM) and DEM of Difference (DoDs, i.e. topographic changes in the Siurana River upstream (u/s) and downstream (d/s) from the dam). The elevation change in blue represents deposition and in red erosion. Note that the thresholded DoDs were elaborated by means of the application of a minimum Level of Detection (minLoD). Briefly, errors in both DEMs were assesed. These errors are propagated and provided a minLoD. Topographic changes below this minLoD are considered uncertain. Only when changes in a given cell are higher than the minLoD are taken into account (see similar approach in Brasington et al., 2003; Wheaton et al., 2010).*

4.3. Invertebrate assemblage structure and species traits

In total, 46 invertebrate taxa were identified, 33 in u/s and 37 in d/s. Taxa richness, density and biomass differed significantly between the two reaches (ANOVA: F= 242, 54 and 72 respectively; p<0.001). The upstream reach showed the lowest mean values (9 taxa, 734 ind m^{-2} and 145 mg m^{-2}), compared with values found in d/s (20 taxa, 31,500 ind m^{-2} and 3,850 mg m^{-2}; Fig. 8). However, the diversity was lower in d/s (3.3) than in u/s (5).

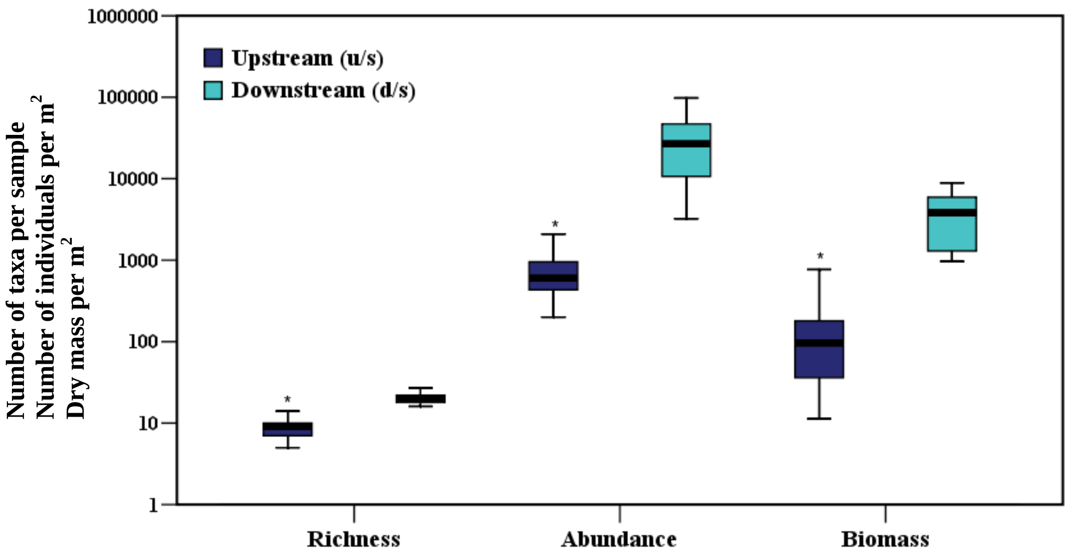

Figure 8. *Box plots of invertebrate richness (number of taxa per sample), abundance (number of individuals per m^2) and biomass (dry mass per m^2) in u/s and d/s. Plot contains the median values (central line of each box), the quantiles 25 and 75 (upper and lower side of the box) together with the non-outlier range (whiskers).*

The most common family at both reaches was Chironomidae, comprising 20% of the community in u/s and 43% in d/s. Furthermore, *EPT* taxa were dominant in u/s (58%) with Plecoptera being the most abundant order, and the genera *Leuctra* sp. comprising approximately 35% of the total abundance, followed by *Baetis* sp. and *Hydropsyche* sp. to a lesser extent (11 and 5%, respectively). In the downstream reach, *EPT* taxa comprised 43% of all individuals, with *Baetis* being the most abundant (32%), followed by *Caenis* sp. and *Leuctra* sp. (3% for each of them). Fourteen of the sixteen taxa common at both reaches showed a density increase in d/s compared with u/s by a factor of 3 or more (Annex 1). Nine of the taxa present in u/s were absent in d/s, with these absentees mostly being species of the Coleoptera and Ephemeroptera orders. However, fifteen new species appeared below the dam, the most abundant being: *Gammarus sp.*, *Potamopyrgus antipodarum*, *Ancylus fluviatilis* and Haplotaxidae. Body size was significantly smaller in u/s for Tanypodinae, *Caenis*, *Habrophlebia*, *Leuctra* and *Polycentropus*, whereas only *Hydropsyche* were larger in u/s (Table 4). In addition, statistically significant differences (p<0.05) between habitat characteristics were observed in u/s, with riffles showing the greatest richness, abundance and dry weight per sample. No taxon was found exclusively in fine sediments. No significant difference in species richness was identified in d/s between both high and low velocity, although abundance and biomass are significantly greater in areas with higher velocity.

Table 4.

ANOVA results to assess the effects of the Siurana dam on the macroinvertebrates' size in the upstream (u/s) and downstream (d/s) study reaches. Table includes results for the most abundant and common species.

Taxon	**Mean size[1] (mm)**	**Mean size[2] (mm)**	**F**	**p-value**
Baetis sp.	0.43	0.47	1.31	0.26
Caenis sp.	0.66	0.77	6.90	0.01*
Habrophlebia sp.	0.59	0.87	6.50	0.03*
Hydropsyche sp.	0.88	0.50	14.19	<0.01**
Leuctra sp.	0.41	0.70	291	<0.01**
Limnius sp.	0.2	0.19	0.04	0.83
Onychogomphus uncatus	1.71	1.09	1.25	0.28
Orthoclodiinae	2.68	2.99	2.96	0.09
Polycentropus sp.	0.66	1.03	17.09	<0.01**
Simulidae	2.36	2.64	0.40	0.53
Tanypodinae	3.2	4.56	25.92	<0.01**

[1]Upstream reach (u/s)
[2] Downstream reach (d/s)
*p<0.05; **p<0.001

The values in Table 5 indicate that there were no gross differences in trait prevalence between u/s and d/s reaches. However, some differences in traits became evident in species present only in either u/s or d/s. The upstream reach supported a greater proportion of taxa with aerial active dissemination, scrapers and crawlers (50%, 51% and 78%, respectively); in contrast, d/s supported communities with greater aquatic dissemination, shredders and swimmers (72, 32 and 35%, respectively).

Table 5.
*Results of seven biological traits following Tachet et al. (2002). Differences in communities were examined in two steps: (i) Comparison of all taxa that constitute the community (columns with *); (ii) Comparison of selected species that are just present either in u/s or d/s (columns with ** i.e. site-specific species).*

Trait	Category	Upstream* (%)	Downstream* (%)	Upstream** (%)	Downstream**(%)
Life cycle duration	≤1 year	71	75	48	62
	>1 year	29	25	52	38
Dissemination	Aquatic passive	32	36	24	43
	Aquatic active	22	26	19	29
	Aerial passive	13	15	7	19
	Aerial active	33	24	50	9
Feeding habits	Deposit feeder	16	15	8	1
	Shredder	20	22	25	32
	Scraper	31	28	51	33
	Filter-feeder	13	13	0	16
	Piercer (plant or animal)	4	3	5	3
	Predator (carver/engulfer/swallower)	15	16	11	14
	Parasite, parasitoid	2	2	0	0
Temperature	Stenotherm:psychoprile (<15ºC)	24	24	11	20
	Stenotherm:thermophil (>15ºC)	7	9	5	10
	Eurytherm	69	67	84	70
Microhabitat	Slabs, blocks, stones, pebbles	19	21	17	26
	Gravel	11	12	7	12
	Sand	10	9	5	6
	Silt	5	5	2	4
	Macrophyte, filamentous algae	23	22	25	17
	Microphite	3	4	7	9
	Branch, roots	11	11	6	10
	Litter	9	8	17	9
	Mud	8	8	13	7
Locomotion and substrate relation	Flier	2	2	2	0
	Surface swimmer	4	4	0	4
	Swimmer	12	17	14	35
	Crawler	53	47	78	33
	Burrower (epibenthic)	10	9	2	3
	Interstician (endobenthic)	9	10	3	9
	Temporarily attached	10	12	0	15
	Permanently attached	0	0	0	0
Flow preferences	Null	17	14	32	17
	Slow (< 0.25 m s^{-1})	30	38	25	31
	Medium (0.25-0.5 m s^{-1})	30	33	28	39
	Fast (> 0.5 m s^{-1})	23	20	15	14

4.4. Hydro-ecological patterns in the Ebro catchment

The first two axes of the RDA relating the hydrological parameters and the invertebrate assemblages (Fig. 9), explained 38% of the total variance in invertebrate composition in the samples and 79.4% of the variation in the community composition which can be accounted for the measured environment variables (p = 0.002 after a Monte Carlo Permutation tests with n=499). Axis 1 (23.4% of the variance) captured the Mediterranean hydrological character of the rivers (i.e. high seasonality and torrentiality), with most of the unregulated sites sitting within the positive portion of the axis. The axis 2 (14.6% of the variance) was mainly positively related to the mean annual *Q* and catchment drainage area while, curiously, *IR* was negatively correlated with flood magnitude (i.e. Q_{ci}).

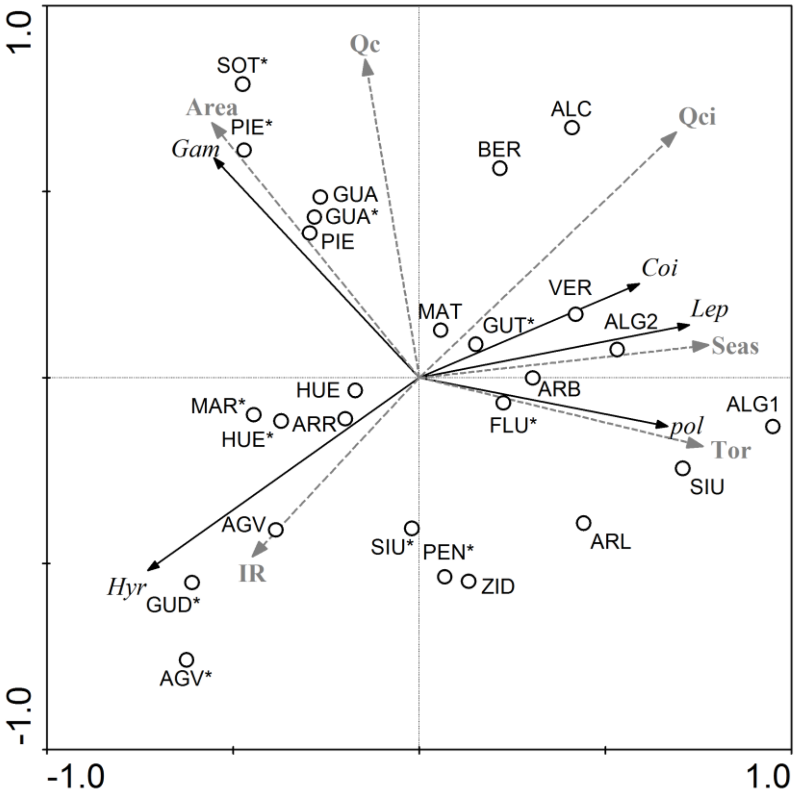

Figure 9. *Redundancy Detrended Analysis (RDA) of the invertebrate communities (i.e. relative abundance data) (Gam: Gammaridae, Hyr: Hydrobiidae, Pol: Polycentropodidae, Lep: Leptophlebiidae, Coi: Corixidae), in relation to distinct hydrological metrics (Q_c, median annual daily discharge; Q_{ci}, median instantaneous maximum discharge; Tor, torrentiality), the drainage area (area) and the degree of regulation (IR) for the 26 reaches selected of the Ebro catchment, including the River Siurana (for more details, see the methods section). The effects of the explanatory variables are highly significant (p=0.002 after 499 permutations). Although analyses are composed by 70 taxa, only those species with a cumulative fit of more than 0.35 are displayed in the plot. The first two axes explained 38% of the total variance in invertebrate composition in the samples and the 80% of the variation in the community composition which can be accounted for the measured environment variables; $^{(*)}$ denotes that the reach is regulated by a dam. Open circles represent the Ebro sites, while the closed ones represent the Siurana sites.*

These results, together with that obtained by the Pearson correlations (Table 6, 7), showed that the Mediterranean reaches (i.e. high values of torrentiality and seasonality) were mainly characterized by *EPT* and *OCH* taxa with traits providing better resistance against disturbance, such as active aerial dispersion (e.g. Caenidae, Polycentropodidae, Leptophlebiidae and Corixidae; p<0.05). In contrast, some other taxa (e.g. Gammaridae, Oligochaeta, Ancylidae and Hydrobiidae; p<0.05) showed negative correlation. Additionally, *IR* affected neither the diversity nor the taxonomic composition, but richness was slightly reduced (Table 7). In turn, torrentiality and seasonality showed a clear positive effect on diversity.

Table 6.
Pearson correlation matrix obtained between macroinvertebrate taxa (i.e. relative abundance), drainage area (i.e. area), impoundment ratio (IR), torrentiality and seasonality of the 26 sites selected in the Ebro basin, including the River Siurana (for more details, see the methods section). Only taxa present in at least 5 sites were taken into account for the analysis.

	Area	***IR***	**Torrentiality**	**Seasonality**
Ancylidae	-0.16	0.52*	-0.22	-0.44*
Caenidae	0.14	-0.17	0.50*	0.40*
Corixidae	-0.12	-0.36	0.51*	0.50*
Chironomidae	-0.46*	-0.24	0.43*	0.26
Dixidae	-0.39*	-0.18	0.16	0.19
Dugesiidae	0.26	-0.05	0.44*	0.23
Dytiscidae	-0.14	-0.01	0.45*	0.22
Erpobdellidae	-0.08	0.46*	-0.25	-0.48*
Gammaridae	0.67**	-0.06	-0.54*	-0.40*
Gomphidae	-0.23	-0.08	0.40*	0.22
Hydracarina	-0.51**	-0.22	0.24	0.33
Heptageniidae	-0.09	-0.30	0.26	0.41*
Hydrobiidae	0.06	0.61**	-0.44*	-0.63**
Hydrophilidae	-0.19	-0.31	0.60*	0.44
Leptophlebiidae	-0.22	-0.38	0.57*	0.65**
Leuctridae	-0.49*	-0.06	0.31	0.13
Naucoridae	0.04	-0.28	0.57*	0.49*
Oligochaeta	0.13	0.15	-0.44*	-0.38
Polycentropodidae	-0.57*	-0.07	0.62**	0.28
Sphaeridae	-0.06	0.47*	-0.22	-0.44*
Stratiomyidae	0.11	-0.34	0.53*	0.49*

*p<0.05; **p<0.001

Table 7.
Pearson correlation matrix between invertebrate metrics, impoundment ratio (IR), torrentiality and seasonality of the twenty-six selected sites in the Ebro basin, including the River Siurana (for more details, see the methods section).

Metrics	*IR*	Torrentiality	Seasonality
Richness	-0.39*	0.15	0.22
Simpson[1]	-0.37	0.46*	0.43*
EPT[2]	-0.34	0.39	0.53*
OCH[3]	-0.23	0.34	0.46*
Others[4]	0.35	-0.45*	-0.62**

*p<0.05; **p<0.001
[1] Simpson's diversity index
[2] Relative abundance of *Ephemeroptera*, *Plecoptera* and *Trichoptera* (*ETP*) in %
[3] Relative abundance of *Odonata*, *Coleoptera* and *Hemiptera* (*OCH*) in %
[4] Relative abundance of the other taxons (neither *ETP* nor *OCH*) in %
[5] *Ephemeroptera*, *Plecoptera* and *Trichoptera* (*ETP*) richness
[6] *Odonata*, *Coleoptera* and *Hemiptera* (*OCH*) richness
[7] Richness of the other taxa (neither *ETP* nor *OCH*)

5. DISCUSSION

The Siurana Dam has altered the flow and thermal regimes of the downstream river. The seasonal flow pattern was inverted and the magnitude and frequency of high flood events were largely reduced, while the mean annual discharge and the total annual runoff remain practically unaltered. Water is released from the hypolimnion which reduces seasonal variation in temperature, as the water released is warmer in winter and colder in summer. Thermal alteration affects growth rate of stream organisms and the life-cycles of certain species (Brown et al., 2004). Together these habitat changes suggest the potential for ecological adjustment in the downstream river.

5.1. Changes in channel habitat and bed stability

Some impacts of flow regulation can be observed soon after dam construction, although more profound habitat adjustments related to river morphology (relevant at the ecosystem level) typically occur over longer periods (10-100 years) after impoundment (Petts et al., 1993; Brandt, 2000; Phillips et al., 2005; Gordon and Meentemeyer, 2006). For instance, Petts and Gurnell (2005) indicated that mobile-bed channels in semiarid areas are highly sensitive to damming since channel changes are accelerated by the rapid response of the riparian vegetation to flood regulation and the establishment of perennial flows. In the case of the Siurana, adjustments of river morphology (i.e. channel form) were evident a short time after the dam construction, as it is clearly shown by the steep decrease in the GS index after thirteen years, resulting in the loss of channel complexity and instream habitat structure (e.g. Magdaleno and Fernández, 2011).

The degree of disturbance during floods is determined by the magnitude of the event in relation to bed sedimentology (i.e. size and structure) and channel geometry. Flash floods are capable of entraining surface sediments and, eventually, mobilize subsurface material, thus keeping the bed active and regularly modifying the physical habitat. The upstream section in the Siurana is a good example of such geomorphic activity. Recent studies have highlighted the importance of disturbance in generating and maintaining an ever-changing habitat mosaic of small bed patches that experience scour, fill or remain invariable after each flood (Matthaei et al., 1999b). Such mechanisms were clearly significant, as shown by the changing erosion and deposition patterns after each event in the u/s section; in contrast, the reduction in flood magnitude in d/s led the river to a *quasi*-inactive situation.

5.2. Changes in invertebrate communities

Comparison of upstream and downstream sites suggests that species composition has been affected by the flow regulation, although there is no evidence of impacts on species richness. Remarkably, density and biomass increased below the dam whereas the diversity index decreased. These changes did not appear to affect the trait composition of the whole community. Trait similarities between communities occur because some biological traits were selected by climatic and environmental characteristics as a large-scale filter of life-cycle traits (Bonada et al., 2007). However, it is important to emphasize that almost all species located in u/s present a terrestrial life stage and are therefore able to exploit both river and terrestrial refuge sites (e.g. Townsend et al., 1997; Hershkovitz and Gasith, 2013). Moreover, for species that occurred only in one reach, the proportion of individuals with aerial active dispersion mechanisms, scrapers and crawlers, was higher in u/s. Aerial dispersion is an important mechanism of invertebrate recolonization following disturbance in headwaters streams so our results are consistent with those of previous studies (Wallace, 1990).

Several works have generally shown that invertebrate density tends to be lower in rivers with frequent floods (Schwendel et al., 2011; Lake, 2000; Robinson, 2012). Frequent large floods in u/s are likely to mobilize the bed sediments, and with them many or most invertebrates (Brittain and Eikeland, 1988; Gibbins et al., 2007). Such involuntary or catastrophic drift is an important reset mechanism in fluvial ecosystems and the persistence of certain species may depend on the occurrence of these events (e.g. Picket and White, 1985; Grimm and Fisher, 1989; Garcia et al., 2012). In the downstream section, the reduced flood magnitude and frequency (i.e. the main consequence being that the bed is seldom perturbed and never becomes fully mobile) allows higher density and biomass of invertebrates than in the upstream reach. Besides, substrate stability, together with stable flows, is typically associated with high amounts of periphytic biomass (Poff et al., 1990), a phenomenon that had been already observed downstream from the Siurana Dam (Ponsatí et al., 2014). Algae supply food and refuge for invertebrates (Moog, 1993) that, together with flow stability, can benefit some species. As in other rivers, for instance in the UK (e.g. Brittain and Salveit, 1989; Armitage, 2006), an increase in algae biomass promotes the abundance of some mayfly species (e.g. *Ephemerella* and *Baeti*s) and Amphipoda (e.g. *Gammarus*), while restricting others which utilize suckers or friction pads for attachment, as in many Heptagenidae (Ward, 1976; Armitage et al., 1987; this study). High food supply and stable conditions may allow individuals to attain the larger body sizes observed at the u/s reach.

Disturbance also affects both short- and long-term distribution of stream organisms (e.g. Nisbet et al., 1997; Matthaei and Townsend, 2000). Our results show that in the unstable upstream reach species composition differed greatly between samples (even within the same habitat). Although we found a total of 33 taxa in the reach, the mean richness per sample was 9 and only one taxon (*Leuctra*) was present in all samples. In the downstream reach, invertebrate distribution was much more homogeneous (i.e. 8 common taxa in all samples which represent more than 90% of the total density). The displacement of competitive species may occur in highly stable environments and some successful species dominate the community although they do not completely eliminate the other species (Death and Winterbourn, 1995). This fact was also observed for biofilms which had more homogeneous distribution in the downstream reach (Ponsatí et al., 2014).

In terms of substrate and hydraulic conditions, the u/s reach was more heterogeneous than the d/s, with d/s having a higher habitat diversity related to aquatic vegetation coverage and other elements (e.g. leaves and branches). In u/s, sand and bedrock show low macroinvertebrate abundance and no exclusive species. Substrate classes which could potentially host the highest macroinvertebrate diversity, richness and abundance (i.e. gravels, cobbles) were similar (same D_{50}) in both reaches (i.e. the entire channel in d/s and the area occupied by gravels in u/s). Therefore, the differences observed in terms of the benthic fauna between study reaches could not be a result of differences in the grain size. Rather, the differences seemed to be driven by bed disturbance, as discussed above. However, reduction of habitat heterogeneity and disturbance promote the colonization of invasive species such as the snail *Potamopyrgus antipodarum* (mean densities of 3000 ind. m^{-2}) in the Siurana, which has been also associated with regulation in the UK (Gillespie et al., 2014).

5.3. Invertebrate communities in the Ebro catchment: a wider Mediterranean context

Results for the whole Ebro catchment (Tables 6 and 7) show that despite all reaches being located in the same general hydroclimatic region, flow regimes influence both the taxonomic and trait composition of the communities: i) reaches that display Mediterranean characteristics (i.e. high torrentiality and seasonality) were dominated by *EPT* and *OCH* taxa whose traits provide resistance against disturbance, such as active aerial dispersal which favours dispersion and recolonization; ii) in turn, reaches with more permanent and stable flow regimes, where higher primary production is expected, were characterized by detritivore species with a fully complete aquatic life-cycle. Moreover, Hydrobiidae was significantly more abundant in impounded streams ($p<0.001$), in agreement with results reported by Gillespie et al. (2014). The distribution of this family is limited by stenotherm conditions (Oscoz et al., 2011), a fact that is highly related to the homogenization of stream temperature caused by dams, as well as the distribution of suitable lentic environments with high organic matter content. Such results were in concordance with those observed at the River Siurana, where regulation has completely changed its hydrological behaviour, shifting from a typical Mediterranean regime to a more permanent and stable flow regime (i.e. low torrentiality and seasonality). Community diversity and assemblage structure changed accordingly, moving from one dominated by *EPT* to another mainly composed of detritivore species with a fully aquatic life-cycle.

To summarize our findings, we present a conceptual model depicting physical and macroinvertebrate responses to relative changes in flood magnitude and sediment dynamics in dammed rivers (Fig. 10), which is fully applicable to Mediterranean rivers. This model includes four scenarios (note that the scenarios are not meant to be consecutive nor dependent): 1) Degradation in which bed incision and coarsening predominate and are caused by competent *clearwater* releases (Kondolf, 1997), that in turn reduce taxa richness, diversity and density of macroinvertebrates (Poff and Zimmerman, 2010); 2) Stability with channel narrowing and vegetation encroachment as the main adjustments (Lobera et al., 2015; González del Tánago et al., 2015), in which taxonomic composition changes by losing native and sensitive species, and macroinvertebrate density increases (Cortes et al., 1998; the Siurana downstream from the reservoir is a good example of this); 3) Quasi-equilibrium, where the system maintains its main features (i.e. in the case of the Mediterranean rivers the high degree of hydrological disturbance keeps the channel geomorphically active), with taxa richness and biodiversity usually high and density low; and 4) Aggradation (or channel infilling) that may be found downstream from dams with high sediment loads and low competent flood events resulting in fine sediment accumulation; this aggradation reduces taxa richness, diversity and macroinvertebrates density, and only high sediment-tolerant species may increase (Wood and Armitage, 1997; Buendia et al., 2013).

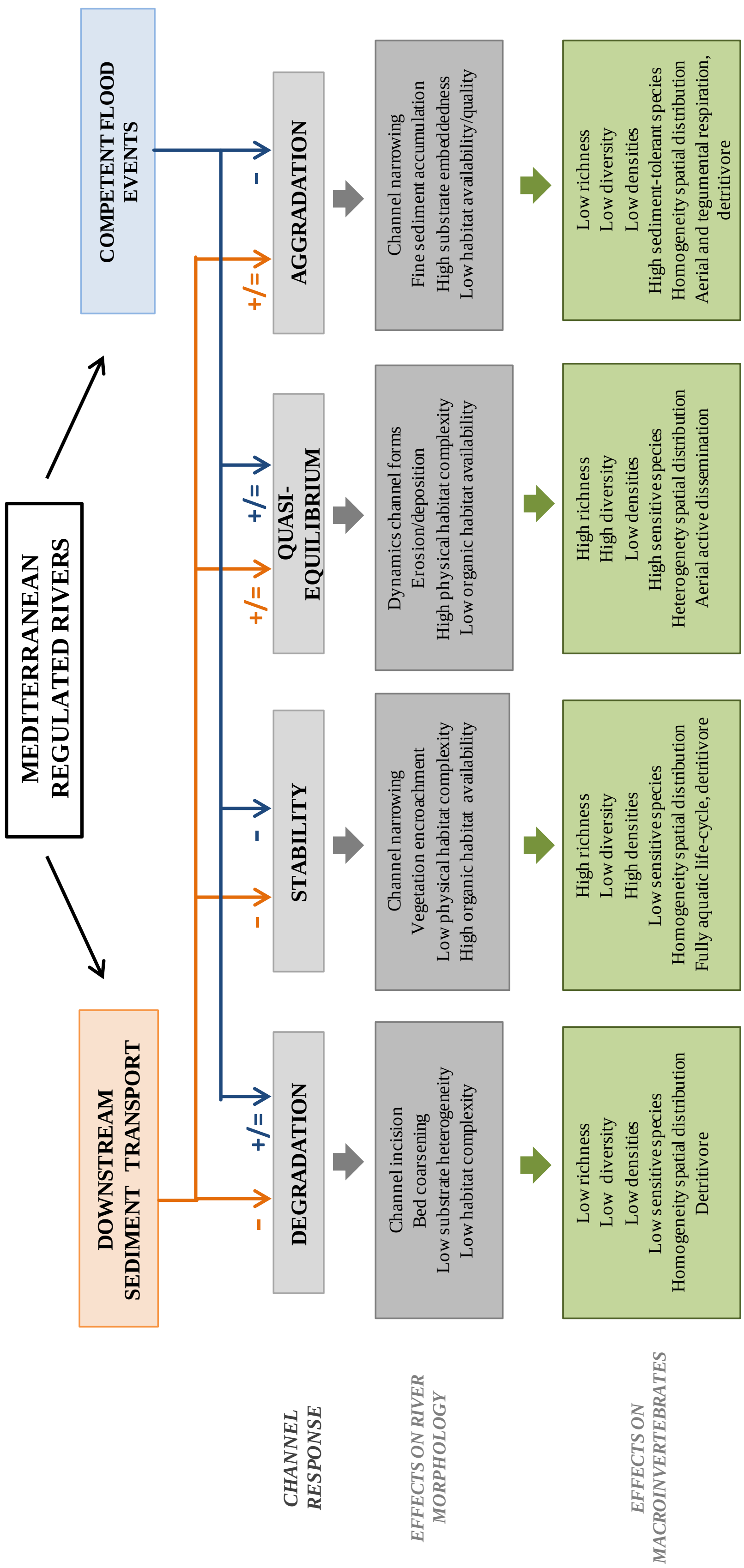

Figure 10. *Conceptual model illustrating changes in physical and biological conditions of a stream in response to an increase or decrease of both flood magnitude and sediment transport in dammed fluvial systems. (-) indicates decrease downstream from dam; (=/+) means that the situation remains equal or increase downstream.*

6. CONCLUSIONS

This paper has aimed at assessing basic geomorphological and ecological (i.e. invertebrates communities) responses to impoundment in the River Siurana, a stream selected as representative of hydroecological characteristics of catchments in the Western Mediterranean region. The main conclusions to be taken from the study are drawn as follows:

i) Regulation of the River Siurana has reduced the variability of its flow regime, which has become permanent and more stable. Upstream from the reservoir, floods have kept the bed active, frequently modifying the physical habitat. Downstream from the dam the river shows almost no geomorphological activity. Water thermal regimes have also been greatly altered.

ii) Benthic invertebrate communities differ significantly in taxonomic composition between the upstream and the downstream reaches. Density and biomass have increased below the dam, although diversity has decreased. These structural changes have not resulted in a biological change of the whole community. However, for site-specific species the proportion of individuals with active aerial dispersion mechanisms i.e. scrapers and crawlers have been reduced below the dam.

iii) Results for the whole Ebro catchment have shown that the effects of flow regulation are consistent with the Siurana results. Taxa with active aerial dispersal trait dominate unregulated reaches with Mediterranean hydrology, and reaches with more permanent and stable flow regimes are characterized by fully aquatic detritivore species.

Finally, our study emphasizes the influence of riverbed dynamics on benthic species distribution and abundance. Thus, physical disturbance needs to be assessed not only in terms of discharge variation but in terms of bed mobility and sedimentary activity (Townsend et al., 1997; Tonkin and Death, 2013). This issue needs to be taken in account fully by river managers in order to maintain the ecological integrity of rivers downstream from large infrastructures such as dams.

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Annex. Results of ANOVA used to assess the effects of dam on macroinvertebrate abundance and composition.

	Mean abundance[1] (number × m^{-2})	**Mean abundance[2] (number × m^{-2})**	**F**	**p-value**
Ancylus fluviatilis		81.3	312.6	<0.00**
Anthomyidae		25.7	27.1	<0.00**
Athericidae	1.5		2.3	0.139
Baetis sp.	75.3	9990.6	99.3	<0.00**
Boyeria irene	4.6		7.85	<0.01*
Caenis sp.	13.6	1015.8	189.7	<0.00**
Centroptilum sp.	5.2		4.2	0.04
Ceratopogoninae	3.1	19.9	9.3	<0.01*
Cyphon sp.	67.9		70.5	<0.00**
Dixa sp.		10.5	15.5	<0.00**
Ecdyonurus sp.	9.3		13.9	<0.00**
Elmis sp.		190.6	175.9	<0.00**
Empididae	0.9	11.7	11.3	<0.00**
Epeorus sp.	1.2		1.0	0.31
Ephemerella sp.	0.9	686.0	1050.7	<0.00**
Gammarus sp.		309.4	525.4	<0.00**
Habrophlebia sp.	2.2	15.8	3.75	0.06
Haplotaxidae		72.5	96.6	<0.00**
Hidracarina		8.2	30.1	<0.00**
Hydrobius sp.	1.5		2.3	0.14
Hydropsyche sp.	38.9	349.1	11.7	<0.00**
Hydroptila sp.	10.2	177.8	25	<0.00**
Leuctra sp.	247.8	829.8	39.0	<0.00**
Limnius sp.	39.2	477.2	51.2	<0.00**
Metalype fragilis		19.3	42.5	<0.00**
Onychogomphus uncatus	3.1	11.7	5.3	0.02
Orthocladiinae	121.0	13025.1	116	<0.00**
Oulimnius sp.	0.9		1.6	0.20
Oxyethira sp.		4.1	9	<0.01*
Pisidium sp.		2.3	1.9	0.17
Polycentropus sp.	4.6	33.3	33.5	<0.01*
Potamopyrgus antipodarum		2966.7	4345.7	<0.00**
Procambarus sp.		2.3	6.4	0.014
Psychodidae		5.3	15.3	<0.00**
Rhyacophila sp.		125.1	42.9	<0.00**
Simulidae	15.7	187.1	18.9	<0.00**
Tanypodinae	24.7	349.7	65.8	<0.00**
Tipulidae	0.9	6.4	8.5	<0.01*
Stratiomyidae	0.9		1.1	0.31
Wormaldia sp.		8.8	15.6	<0.00**

[1] Upstream reach (u/s)
[2] Upstream reach (d/s)
*p<0.05; **p<0.001

Chapter 7

1. DISCUSSION

Mediterranean rivers are characterized by marked hydrological fluctuations, which is an important characteristic that affect the geomorphology, ecology and human uses of these river systems (Puckridge et al., 1998). Their seasonal and inter-annual flow variability are essential to sustain their native aquatic organisms and riparian vegetation, as well as their physical habitats (Kondolf and Batalla, 2005). Therefore, Mediterranean rivers are ecologically unique, contain great biodiversity and high levels of endemism (Bonada and Resh, 2013). Unfortunately, anthropogenic disturbances are numerous in Mediterranean regions and aquatic fauna are declining more rapidly than anywhere else in the world (Moyle and Leidy, 1992). Their seasonal and unpredictable precipitation pattern are a great inconvenience for human uses, and so water availability and demand are most of the time out-of-phase. Consequently, Mediterranean rivers are widely impounded to maintain reliable water supply.

Large climatic heterogeneity can be found along short distances in Mediterranean climate region, encompassing elevated areas with annual rainfall exceeding 1000 mm to semi and arid areas with 200 – 500 mm y^{-1}. Then, different flow categories can be differentiated in Mediterranean streams: permanent, intermittent and ephemeral streams. As a result of this variability, the present study was carried out across four large basins in the Iberian Peninsula in order to assess general patterns of Mediterranean regulated rivers. Dams produce a generalized decrease in the annual stream flow and in the magnitude and frequency of floods (thus flow competence). This decrease is especially apparent for low-magnitude events (i.e. Q_2), which are considered the dominant channel forming discharge. Furthermore, dams produce a complete inversion of natural seasonal patterns due to water is required for agricultural irrigation during the dry summer months. Results of the study are in agreement with those described in the literature in the Ebro basin (Batalla et al., 2004) and other Mediterranean-climate regions (Kondolf and Batalla, 2005; Grantham et al., 2013). However, hydrological changes were also observed in rivers which were not affected by dams during the 20th Century. These change may reflected the influence of other factors such as land cover changes (Gallart and Llorens, 2004; López-Moreno et al., 2006; Buendía et al., 2015) or climate change (Morán-Tejeda et al., 2011; Lorenzo-Lacruz et al., 2012).

The immediate result after dam building is the channel degradation and, over time, a complete transformation of the channel morphology according to the new water discharge and sediment load conditions (Petts and Gurnell, 2005; Vericat and Batalla, 2006). Our results show that only reaches with little or no regulation maintain exposed sedimentary deposits. Reduction of channel processes (i.e. flow competence) favours the encroachment of vegetation in formerly active areas, which is a well-known phenomenon (e.g. Williams and Wolman, 1984; Petts and Gurnell, 2005; Vericat and Batalla, 2005). The stabilization limits river dynamics and contributes to the environmental degradation of the fluvial ecosystem (e.g. Magdaleno et al., 2012), thus reducing the habitat for aquatic and riparian wildlife (Graf, 2006). A Geomorphic Status (GS) index that allows assessment the dynamism of a river reach and its change through time is presented as a new tool to assess river responses to regulation. Accordingly, the GS declines with magnitude of the impoundment. Headwater sites are especially affected by damming, which reduces their dynamism and making them more similar to low-energy lowland rivers with highly stable beds.

Mediterranean and mountainous regions have generally higher suspended sediment yields (*SSY*) than temperate or lowland ones. Quantitative assessment of the human impact in such regions is therefore important (Vanmaercke et al., 2011). This is the reason why the Ésera and Siurana rivers were selected for the present work. The River Ésera yielded a mean runoff of 524 mm y^{-1}, with 37 flood events being observed during the 2-yr study period (Q_{max} = 477 m^3 s^{-1}). Mean annual suspended sediment load was 303,252 t y^{-1}, giving a *SSY* of 337 t km^{-2} y^{-1}. This value is much lower than in the nested River Isábena, with a mean *SSY* of ca. 600 t km^{-2} y^{-1} for the period 2005-2010 (López-Tarazón and Batalla, 2014). This issue can be attributed to geological/lithological factors, especially to the specific area that is comprised of badlands, being more important in the Isábena rather than the Ésera. Furthermore, the badland area is directly connected with the fluvial network in the Isábena through its main tributaries, whereas in the Ésera this connection is mainly established with relatively small tributaries which are usually dried up (López-Tarazón et al., 2015). Overall, and despite the difference observed regarding the incoming runoff (i.e. 550 hm^3 in the case of the Ésera and 170 hm^3 in the case of the Isábena), the relative contribution of the River Ésera to the entire sediment yield coming into the Barasona reservoir is just ca. 55% if both the short- (i.e. the single year 2011-2012; López-Tarazón et al., 2015) and long-term (López-Tarazón and Batalla, 2014) time scales are considered. This is in clear disaccord with the results obtained by Alatorre et al. (2010), who estimated a sediment yield contribution of the River Ésera to the Barasona reservoir of around 70% by using the sediment delivery model WATEM/SEDEM. This fact emphasizes the difficulty of estimating sediment fluxes in catchments as dynamic as the Ésera and the importance of intensive and high frequency field monitoring. Furthermore, floods are responsible of 2/3 of the annual load, a fact that points out the important role of baseflows in the export of sediment from the basin (similar as in the case of the River Isábena; López-Tarazón et al., 2011).

Mean runoff in the River Siurana was 5 hm^3, and just 6 events occurred during the study period (Q_{max} = 33 m^3 s^{-1}). Mean annual sediment load was 369 t y^{-1}, giving a *SSY* of 11 t km^{-2} y^{-1}. This value is lower than the described by Walling and Webb (1983, 1996) for Mediterranean basins in the Iberian Peninsula (100-200 t km^{-2} y^{-1}) and other European watersheds (e.g. Vanmaercke et al., 2011). The largest proportion of the suspended sediment is transported by floods, highlighting the strong Mediterranean character of the catchment. Similar patterns were described in other similar-sized Mediterranean catchments (e.g. Estrany et al., 2009; Tena and Batalla, 2013). However, the suspended sediment concentrations are rather low (SSC_{max} = 2.5 g l^{-1}), owing to the low-intensity erosion processes in the catchment. This phenomenon may be attributed to the fact that the Siurana basin is a sediment-limited system, hence supplying only small amounts of sediment.

Results have shown that the reservoirs of the rivers Ésera and Siurana reduce the sediment load by 2 orders of magnitude at the downstream monitoring sites, although the total runoff is only reduced in the case of the Ésera (i.e. 82% of the water is derived through to the Canal of Aragón and Cataluña). However, the Barasona Reservoir alters the hydro-sedimentological behaviour of the River Ésera, shifting it from a humid mountainous regime to a semi-arid climate type of river, in which most of the water and sediment load is associated with few flood events (in this case, dam releases). In the case of the Siurana, the reservoir exerts the opposite effect, changing the sediment and flow regimes of the river from a typical Mediterranean behaviour to a more permanent and stable flow typical of less-arid regions. Furthermore, sedimentation in Barasona during the study period (including the River Isábena; López-Tarazón and Batalla, 2014) attained 550,000 t y^{-1}, while in the Siurana reservoir it was just 330 t y^{-1}.

The frequency and magnitude of physical disturbance (i.e. bed instability) control habitat integrity and, consequently, the ecological diversity of a particular fluvial system (Petts, 2000). In the River Ésera (i.e. a gravel-bed river), surface particles are frequently moved according to the flood magnitude (i.e. size-selective transport) in agreement with the morphological changes observed after each high event. However, the river channel is potentially degraded (i.e. balance between erosion and deposition was always negative), suggesting that a large reduction of the sediment supply within the catchment (it has been widely affected by gravel mining) may produce a degradation trend (Fuller and Basher, 2013). Downstream from the dam, the topographical changes were of the same order of magnitude as the upstream reach, but they only happened once and were associated with the single competent flood which occurred during the study period. Interestingly, the river bed coarsened after this event, probably as a consequence of the winnowing of the remaining fine gravels in the bed surface (i.e. *hungry water* effect, as described by Kondolf, 1997). In the River Siurana (i.e. a sandy-gravel bed river), flash floods are capable of setting the streambed in motion frequently, a fact which can be appreciated through the movement of the recovered tracers, although the morphological changes were rather small (in the range of the median particle size). In this case, the morphological approach underestimates the degree of bed disturbance, likely because a compensation effect of scouring and filling between surveys (Ashmore and Church, 1998; Fuller and Basher, 2013). Below the dam, particle movement and morphological changes were almost nonexistent during the study period, so the reach can be considered quasi-inactive geomorphologically. Such channel stability seems to have existed since the dam was constructed, and has resulted in a severe channel degradation (i.e. large reduction of active channel width and sedimentary structure). This result is in total concordance with those obtained for the whole Iberian Peninsula (Lobera et al., 2015).

Macroinvertebrate communities are directly affected by changes in substrate composition and streambed stability, and are often good indicators of long-term changes in the environment (Beisel et al., 2000; Matthaei and Townsend, 2000; Zhao et al., 2015). Previous studies have generally shown that bed stability allows higher invertebrate density and peryphyton biomass (Schwendel et al., 2011; Lake, 2000; Robinson, 2012), which is in agreement with our results in the River Siurana (Ponsatí et al., 2014; Lobera et al.,2016). Furthermore, the invertebrate community composition in this river shifted due to regulation, but the total number of species remained almost the same. This change can be attributed to the fact that the persistence of certain specialist species may depend on the occurrence of disturbance (Garcia et al., 2012) and to that the increase of algae biomass promotes the abundance of some mayflies (e.g. Ephemerella and Baetis) and Amphipoda (e.g. Gammarus), but restricts others, e.g. many Heptagenidae (Ward, 1976; Armitage et al., 1987; Lobera et al., submitted). In addition, impoundment favours the colonization of invasive species such as the snail *Potamopyrgus antipodarum*, which has been also associated with regulation in the UK (Gillespie et al., 2014). However, these structural changes on the biota do not result in a functional change of the whole community, which may occur because the large-scale filter of life-cycle traits in Mediterranean Rivers (Bonada et al., 2007).

Several studies have reported negative relations between flood disturbance and invertebrates taxon richness (Death and Winterbourn, 1995; Death, 2002), whereas other studies were consistent with the intermediate disturbance hypothesis (i.e. diversity should peak at sites of intermediate disturbance; Ward and Stanford, 1983; Townsend, 1997). Resilience (i.e. the ability to recover from a disturbance) and resistance (i.e. the ability to not succumb to a disturbance) are common attributes found in the Mediterranean biota (Bonada and Resh, 2013; Hershkovitz and Gasith, 2013). In the River Siurana, macroinvertebrate diversity is higher in the upstream reach (highly-disturbed stream), which is in concordance with the results obtained in 26 reaches along the Ebro Basin (Lobera et al., 2016). According to this study of the whole Ebro basin, the reaches that preserve Mediterranean features were significantly dominated by EPT and OCH taxa with traits permitting better resistance against disturbance, such as active aerial dispersal which clearly favors dispersion and rapid recolonization. Therefore, the present study emphasizes the importance of natural flow regime and sediment dynamics for benthic species, and hence that disturbance needs to be measured not only in terms of discharge variation but in terms of bed movement.

A number of studies forecast a decrease in precipitation but an increase in temperature over time as a consequence of climate change (IPCC, 2007) together with acute land-use changes (Morán-Tejeda et al., 2010; Nadal-Romero et al., 2012) which are going to produce a negative evolution of main river flows (Mimikou et al., 2000; Gallart et al., 2011). On the other hand, torrential rainfall events, which are those transporting the majority of sediment, show a significant increase in Mediterranean regions (Alpert et al., 2002). Therefore, it can be expected that reservoir's sedimentation processes are going to increase, hence reducing progressively (but at a higher rate) the impounding water volume. Furthermore, sediment yield and dynamics (Bussi et al., 2014), and stream biota (Filipe et al., 2013) is expected to be altered by climate change in Mediterranean-climate-regions. Reduction in precipitation will lead to an increase of bed stability and hence a modification of the stream biota (Ponsatí et al., 2014; Lobera et al., submitted), while extreme (but more frequent) torrential events will provoke a dramatic alteration on the channel morphology (channel reforming; Church, 2002) and hence resetting the ecological conditions (i.e. catastrophic drift; Gibbins et al., 2007). Recent observations indicated that stream biota tends to be displaced towards higher elevations, and communities tend to change their composition and homogenize, in order to face climate change in Mediterranean regions (Filipe et al., 2013). Keeping this in mind, together with the results obtained by the present thesis, it is probably the moment for Water Authorities and stakeholders to make a step forward and develop new, up-to-date reservoir management procedures, especially at those dedicated to hydropower production, flood control, irrigation and water supply in order to attenuate reservoir sedimentation and downstream effects on the structure and function of the fluvial ecosystem.

2. CONCLUSIONS

The main findings of this thesis corroborate the three hypothesis listed in chapter 1. Conclusions from this PhD thesis can be drawn as follows:

1. A new index has been developed in order to evaluate the physical structure of a given channel reach and its change through time: the Geomorphic Status index (GS). The GS encompasses change in sedimentary units, sediment availability, bar stability and channel flow capacity. It complements the available hydrological indices and may aid further developments of the current tools to characterise the hydromorphology of altered systems, as is required by the River Basin Management Plans.

2. Dams in Iberian rivers produce a generalized reduction of the magnitude and frequency of floods (thus the flow competence). This, in addition to the interruption of sediment transfer downstream, results in the reduction of the geomorphic dynamism (i.e. hence GS) as can be seen by the channel stabilization or degradation associated with the loss of active bars and by vegetation encroachment.

3. Flow regime, suspended sediment patterns and loads are highly variable within the Mediterranean climate streams. Therefore, dam effects are largely variable too, being dependent on the upstream water and sediment supply, the size of the reservoir and its management. Dams altered the hydro-sedimentological behaviour of the study rivers by reducing their sediment loads two orders of magnitude (or more), and shifting their character from one climate-type of river to the opposite (e.g. from a humid-mountainous river to a semi-arid one).

4. Mediterranean rivers are highly-disturbed systems; hence the assessment of stability is essential in such systems. Approaches that integrate more than one measurement (e.g. bed mobility and morphological changes) are able to incorporate different aspects of bed disturbance so they will also likely have stronger relationships with the biota.

5. Bed stability due to regulation causes a significant change in taxonomic composition of the benthic invertebrate communities and increase their density and biomass, while decreasing diversity.

6. Water and sediment management strategies in regulated rivers require a specific assessment in the maintenance of the natural hydromorphological variation and sediment supply in order to reduce downstream effects on the

structure and function of the fluvial ecosystem and, further downstream, onto coastal zones.

3. LIMITATIONS OF THE THESIS AND FUTURE WORKS

Limitations in the methodological design or field work have been identified in each of the chapters. Accordingly, there remain a number of areas that require improvement or further investigation.

Chapter 3 evaluated the effects of regulation on the channel geomorphology in 74 study sites (SCARCE project study sites). However, only 46 sites provided the required data to perform the hydrological analysis, and only in 42 sites it was possible to carry out the geomorphic analysis. Then, the relation between hydrological and geomorphological responses to river regulation was established just in 19 study sites. In order to enhance the study and encompass the spatial variability within the Mediterranean region, additional appropriate study sites would be needed. To obtain this goal it would be necessary to limit the selection of sites to their proximity to a gauging station and make a previous historical analisis of the aerial images, as it was observed that at the end of 1970s (i.e. the image that was used as reference for the geormorphological analysis) many of the sites were already impacted, so an images previous to the dam construction is required.

Chapter 4 analyzed the water and suspended sediment dynamics in two Mediterranean impounded rivers during two years. Limitations in suspended sediment measurements (e.g. turbidimeter calibration, malfunctioning into the instrumentation) together with discharge measurements (e.g. direct flow measure during floods), were the main limitations of this monitoring work. Furthermore, due to the high inter-annual variability of flow discharge in Mediterranean rivers, these findings may not be directly extrapolated to other years or find long-term patterns. This way, sampling should be extended to the longest possible period.

Chapter 5 examined patterns of bed disturbance using the assessment of bed mobility and morphological changes (channel topography). Bed mobility was estimated by means of two types of tracers: painted particles (in all study sites) and particles with Radio Frequency Identification (RFID) tags (just in one site). However, the low recovery rate of painted tracers after high flood events limited the correct assessment of the thresholds of both particle entrainment and transport distance, especially in the site located upstream of Barasona (River Ésera). Accordingly, a combination of different methods of tracer particles (e.g. painted, metal, magnetic, RFID; Schwendel et al., 2010) should be considered for all the study sites in order to obtain a better representation of the degree of substrate disturbance.

Chapter 6 linked substrate stability with invertebrate community structure and function in a Mediterranean regulated river. Although results from the intensive sampling campaign showed clear differences between upstream and downstream invertebrate communities, high inter-annual variability in such communities has been also observed in Mediterranean rivers (Gasith and Resh, 1999). This way, the invertebrate assemblage should be studied, at least, over a year with a different hydrologic disturbance regime. Furthermore, we complemented this single-study by assessing the influence of dams on invertebrate assemblages in 26 reaches in the Ebro basin belonging to the same ecological region of the Siurana. However, this data set was composed of relative invertebrate abundance to family level, so was not possible to examined densities, more highly resolved taxonomic composition (i.e. identified at genus or species level) or trait-based metrics. Therefore, more research of the influence of bed stability due to regulation in invertebrate communities is required in order to find general patterns. To include the whole variability of the Mediterranean rivers, research should be extended both spatially and temporally.

Climate alterations have already been observed during the last decades, and include an increase in frequency, intensity, and duration of extreme events, such as floods or droughts (Milly et al., 2005; EEA, 2008). This effects the frequency and magnitude of soil erosion and sediment redistribution (Bussi et al., 2014), and together with the new flow regime, river systems have to adjust towards a new quasi-equilibrium condition. Therefore, long-term studies are needed to evaluate the effects of climate change on the sediment dynamics, channel morphology, bed disturbance, and the subsequent responses of stream biota and hence update and enhance current water management procedures.

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ANNEX

Annex 1

Suspended sediment, carbon and nitrogen transport in a regulated Pyrenean River

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ABSTRACT

Regulation alters the characteristics of rivers by transforming parts of them into lakes, affecting their hydrology and also the physical, chemical, and biological characteristics and dynamics. Reservoirs have proven to be very effective retaining particulate materials, thereby avoiding the downstream transport of suspended sediment and the chemical substances associated with it (e.g. Carbon, C, or Nitrogen, N). The study of fluvial transport of C and N is of great interest since river load represents a major link to the global C and N cycles. Moreover, reservoirs are the most important sinks for organic carbon among inland waters and have a potential significance as nitrogen sinks. In this respect, this paper investigates the effects of a Pyrenean reservoir on the runoff, suspended sediment, C and N derived from the highly active Ésera and Isábena rivers. Key findings indicate that the reservoir causes a considerable impact on the Ésera–Isábena river fluxes, reducing them dramatically as almost all the inputs are retained within the reservoir. Despite the very dry study year (2011–2012), it can be calculated that almost 300,000 t of suspended sediment were deposited into the Barasona Reservoir, from which more than 16,000 were C (i.e. 2200 t as organic C) and 222 t were N. These values may not be seen as remarkable in a wider global context but, assuming that around 30 hm^3 of sediment are currently stored in the reservoir, figures would increase up to ca. 2.6×10^6 t of C (i.e. 360,000 t of organic C) and 35,000 t of N. Nevertheless, these values are indicative and should be treated with caution as there is incomplete understanding of all the processes which affect C and N. Further investigation to establish a more complete picture of C and N yields and budgets by monitoring the different processes involved is essential.

1. INTRODUCTION

Worldwide, 100,000 km^3 of fresh water is stored in rivers, natural lakes and reservoirs, representing 0.3% of the total fresh water resources. The number of reservoirs increases around 1% per year (Downing et al., 2006), outnumbering natural lakes and storing more than 7000 km^3 of fresh water compared with the just 2100 km^3 stored in natural rivers (Morris and Fan, 1997). Reservoirs are usually very effective at retaining materials, thereby avoiding the downstream transport of suspended sediment and all the different substances associated with it, such as heavy metals (Meybeck et al., 2007; Horowitz, 2008) or nutrients, e.g. nitrogen or carbon (Owens and Walling, 2002; Némery and Garnier, 2007).

Regulation changes the characteristics of certain parts of the water body from “river” to “lake”, affecting not only the hydrology but also the physical, chemical, and biological characteristics of the streamflow. Apart from modifying the natural flow regime (Batalla et al., 2004) and increasing the residence time of the water (Andradottir et al., 2012), streamflow damming alters the seasonal fluctuations (and stratification) of water temperature (Webb and Walling, 1997; Jackson et al., 2007), solute chemistry (Hannan, 1979; Kelly, 2001; Miller, 2012), oxygen content (Marcé and Armengol, 2010), nutrient loading (Marcé et al., 2005; Hou et al., 2014; Knoll et al., 2014), and sediment transport (Vericat and Batalla, 2006; Tena and Batalla, 2013). Moreover, the reduction in water turbulence (i.e. lamination of the stream flow) induced by the lake (reservoir) can lead to an increase in autochthonous primary production (Friedl and Wüest, 2002), and thus to eutrophication of the water mass. In addition to having a global effect on natural water resources, reservoirs alter the natural biogeochemical cycles of carbon, nutrients and metals (Jossette et al., 1999; Teodoru and Wehrli, 2005; David et al., 2006; Cole et al., 2007; Harrison et al., 2009; López et al., 2009). Consequently, altogether these facts result in deleterious effects downstream in the river, where the trophic structure and function of ecosystems such as wetlands, estuaries, deltas and adjacent coastline areas are altered (Armitage, 2006; Larsen and Ormerod, 2014; Ponsatí et al., 2015).

Inland waters are important regulators of sediment, carbon (hereafter C) (especially organic carbon; hereafter OC) which is a significant component in the global C cycle (Meybeck, 1982; Ludwig et al., 1996) and nutrient transport from land to ocean (Cole et al., 2007; Seitzinger et al., 2005; Vörösmarty et al., 2003), at both regional and global scales. Reservoirs trap river sediments transported from the continents to the coastal zone (Bauer et al., 2013), with an estimated retention of 50% of the sediment load which would be naturally delivered to the oceans (Vörösmarty et al., 2003; Walling, 2006) altogether representing a potentially large regional or global C sink (Cole et al., 2007; Tranvik et al., 2009; Gudasz et al., 2010). The study of fluvial C is of great interest since erosion from land to rivers constitutes a very important part of the load of C to the oceans. As a consequence, fluvial C loads represent a major link to the global

C cycle (Degens et al., 1984; Meybeck, 1993). Reservoirs are the most important sinks of OC via sediment deposition (>80% of the total load of 0.2 × 10^9 tC y^{-1}), with inland waters being the most important source of CO_2 emissions (>40% of the total contribution of inland waters of 0.8 × 10^9 tCy^{-1}) (Cole et al., 2007). Similar to C, reservoirs also withdraw nitrogen (hereafter N) from downstream transport (Harrison et al., 2009) and even act temporarily as nutrient sources (Teodoru and Wehrli, 2005). Small lentic waterbodies can have a potential significance as N sinks, as they account for up to half the estimated load (>20 × 10^6 tNy^{-1}) that is retained globally by lakes and reservoirs (Harrison et al., 2009). Most retained N is expected to be lost from the waterbodies via denitrification, but permanent burial in sediments may also constitute a significant N pathway (Saunders and Kalff, 2001; Harrison et al., 2009). Taken together, we may expect reservoirs situated in agricultural lands with large nutrient and sediment inputs to be of major biogeochemical significance.

The aim of this paper is to investigate, at different timescales, the effect that the Barasona reservoir has on the runoff, suspended sediment and associated C and N fluxes from the highly active inflowing River Ésera and its main tributary Isábena, during the hydrological year 2011–2012. Temporal dynamics followed by sediments, C and N have been also determined, analysing the seasonal contribution of the sedimentary and nutrients fluxes. Finally, we expect to corroborate the well-known fact that fluxes draining into the Barasona are (mainly) retained by the dam, so the reservoir acts as an enormous sink of suspended sediment and nutrients, hence altering the sediment budget of the River Ésera catchment and associated biogeochemical cycles.

This study, in conjunction with the work carried out by López et al. (this volume),represents the first steps to establish the C and N cycles in the reservoir together with the processes which modulate organic matter accumulation. These issues have been largely ignored despite their great importance from the ecological and also socioeconomic points of view. In addition to improving the knowledge of the fluxes (and their characteristics) which flow through the Barasona Reservoir (and at a wider scale of most Mediterranean and Pyrenean reservoirs draining highly erodible lands), we intend to establish a basis for future research to extend, refine and update our results to finally establish the complete biogeochemical cycles of the most relevant organic components (e.g. C, N, P).

2. STUDY AREA

The Ésera is a river basin located at the Southern Central part of the Pyrenees. It is the most important tributary of the River Cinca, altogether the second largest tributary of the River Ebro (Fig. 1). The Ésera basin accounts for 1484 km^2, 96% of which are impounded by the Barasona Reservoir. The main tributary of the Ésera is the River Isábena (445 km^2); both catchments are responsible for the remarkable siltation of the Barasona Reservoir. Sediments originate mainly from the middle part of both basins

(Fig. 1), in a corridor consisting of valleys excavated over Eocene marls with sandstones; marls reach the surface in badland structures, with a very high contact surface, being the main sediment sources of the catchments (López-Tarazón et al., 2009) despite their small area (<1% of the total catchment area in the case of the Isábena).

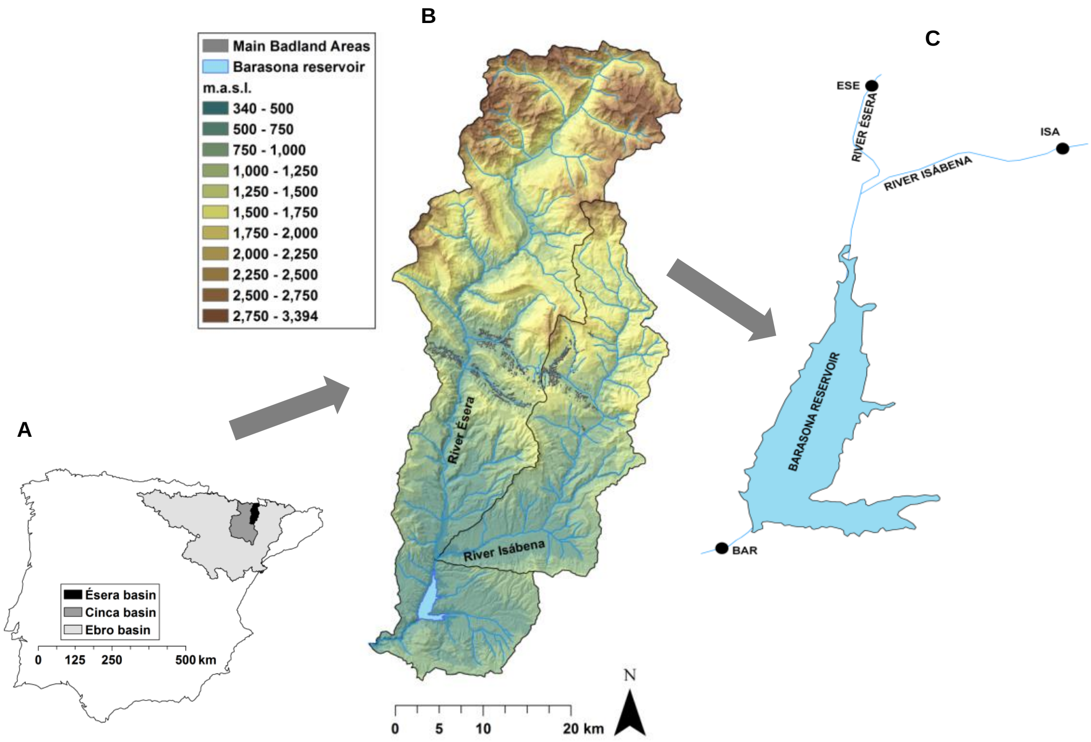

Fig. 1. (A) Location of the Ésera catchment within the Cinca and Ebro river basins in Spain. (B) Map of elevations of the Barasona basin in which the Ésera and Isábena river basins have been differentiated; the grey areas located in the middle zone represent the stripe of marls which reach the surface in a badland structure being the most important source of suspended sediment flowing into the reservoir (López-Tarazón et al., 2009). (C) Detail of the Barasona reservoir in which the monitoring points used in the present work to control the water and suspended sediment that flows into and out of the reservoir have been highlighted (i.e. ESE, ISA and BAR).

The catchment altitude ranges from <400 m above sea level (a.s.l.) at the outlet to >3400 m a.s.l. in the headwaters peaks (i.e., basin mean elevation is 1313 m a.s.l.), exhibiting a characteristic abrupt topography. The area has a Continental Mediterranean climate, wet and cold, with both Atlantic and Mediterranean influences (García-Ruiz et al., 2001). Accordingly, the notable topographic heterogeneity of the basin, with marked temperature and precipitation gradients (both North and Westwards), results in high spatial variability in annual precipitation, with rainfall ranging from >2500 mm y^{-1} at the headwaters to 420 mm y^{-1} in the valley bottom (i.e. mean annual value of 1069 mm y^{-1}). The hydrology of the basin is characterized by a nivopluvial hydrological regime with floods normally taking place in spring (due to snowmelt), and in late summer and autumn as a consequence of localized thunderstorms. However, both high inter-annual irregularity and remarkable discharge variations are observed, a fact especially important in the case of the River Isábena as it is a fully non-regulated river. Conversely, discharge is more constant in the River Ésera as it has small reservoirs (i.e. weirs), canals, and dams for hydropower purposes. Despite the natural discharge regime, the river has been partially modified (e.g. small hydropeaks are created every day in relation to power demand of the nearby villages).

The Ésera represents around 75% of the water flowing into the Barasona Reservoir, while the Isábena accounts for the other 25%. The mean annual discharge of the River Ésera is 18.5 $m^3 s^{-1}$ with a maximum instantaneous discharge of 995 $m^3 s^{-1}$ (return period of 279 years). In contrast, the mean annual discharge of the Isábena basin is 4.1 $m^3 s^{-1}$ with a maximum instantaneous discharge of 370 $m^3 s^{-1}$ (return period of 94 years). Both maximum values were recorded in August 1963, whereas return periods were calculated by the Gumbel method from the series of annual maximum instantaneous discharge for the period 1949–2007 in the case of the Ésera, and 1945–2009 in the case of the Isábena. Finally, the water running along the river channel downstream of the dam is very low and stable during the year at around 0.3 $m^3 s^{-1}$ (i.e. the flow just exceeded 1 $m^3 s^{-1}$ on average during 33 days per year for the period 1991–2013). This is mainly due to the fact that the water flowing through the river channel downstream of the dam is supported by wall filtrations and overflows (the main purpose of the Barasona Reservoir is irrigation so all the water stored is driven by the Canal of Aragón and Cataluña during irrigation seasons). However, a maximum discharge of 505 $m^3 s^{-1}$ was recorded in 1997 corresponding to a return period of ca. 100 years (i.e. Gumbel method applied to the series of annual maximum daily discharge for the period 1991–2013).

3. METHODOLOGY

3.1. Field monitoring

Three gauging stations with continuous monitoring were used in this study, two of them located close to the tail of the Barasona Reservoir (i.e. ESE and ISA, see Fig. 1 for location) to measure flows of water and sediment draining into it, and a third one located immediately downstream from the dam (i.e. BAR) to measure flows draining out of the reservoir (Fig. 1). ESE and ISA were set up in the existing official gauging stations operated by the Ebro Water Authorities (hereafter CHE) (i.e. EA013 and EA047 respectively). Discharge (hereafter *Q*) data for these stations were obtained after calibrating and transforming the continuous 15-min water stage (hereafter *h*) records provided by the CHE into *Q* by the *h/Q* rating curves we produced for each site. *Q* data in BAR were obtained from a capacitive water stage sensor/logger (WT-

HR, TruTrack® Ltd) which was installed at a suitable cross-section (at around 300 m downstream of the dam) to measure *h*. Sensor bias was estimated at ≈10% by comparing real flow gaugings with sensor readings obtained during frequent field visits for instrument maintenance, and episodically during flood events. Stage was then recorded at 15 min intervals and later converted to *Q* by means of the corresponding *h/Q* rating curve. In all cases, rating curves were obtained by combining the stage–mean velocity and stage–area methods for different flow conditions, from baseflow to high magnitude flood events (for more information on the method see López-Tarazón et al., 2012).

Suspended sediment transport was monitored at the three sites continuously as turbidity, which was later transformed into suspended sediment concentration (hereafter *SSC*) by taking a number of water samples during baseflow and floods of different magnitude at all three sites (see next section for the method). High range backscattering Endress + Hauser® Turbimax WCUS41 (Endress + Hauser AG) turbi-dimeters (measuring range up to 300 g l^{-1}) were used in ESE and ISA, due to the anticipated high *SSC* values (see López-Tarazón et al., 2009), while an optical ANALITE® NEP9350 (Planet-Ocean Ltd) turbidimeter (range 0–3000 NTU, ≈3 g l^{-1}) was used in BAR where low *SSC* was expected due to the very low flow that usually runs through the river channel and the reduced (or zero) water released by the dam. All turbidimeters were connected to Campbell® CR-510 (Campbell Scientific Inc.) data loggers recording the turbidity values every 15 min from averages of 5-sec instrument readings.

Sediments were sampled for two different purposes and following two different strategies. First, samples used to calibrate the turbidimeters (and hence to get the continuous *SSC* record) were collected regularly and during floods throughout the study period (hydrological year 2011–2012). Secondly, samples to determine C and N content in the sediment were taken from the sample series to cover representative flow conditions. Three different flow conditions (i.e. low-flows, medium-flows and high-flows) were determined at ESE and ISA after calculating the accumulated frequency curves of the discharge registers for the period 1945–2014. Low-flow was computed as the discharge that is exceeded 95% of the time (i.e. Q_5, 5 m^3 s^{-1} in ESE and 0.7 m^3 s^{-1} in ISA), high-flow was calculated as the discharge that is exceeded just 5% of the time (i.e. Q_{95},45 m^3 s^{-1} in ESE and 16 m^3 s^{-1} in ISA), while medium-flow was established as all the discharge values larger than low-flow but lower than high-flow (i.e. Q_{50}). One condition (i.e. normal-flow) was considered in BAR since flow changes very little through time.

Sediment samples were taken by means of automatic and manual water sampling. Automatic water samples were obtained by ISCO® 3700 samplers (hereafter ISCO), which were triggered by a level actuator to start sampling at a designated water stage at the onset of flood events. In addition, depth-integrated manual water samples were collected weekly and during baseflows, but also during particular floods. Because of the highly turbulent flow conditions (especially during floods) mixing was assumed complete as indicated by various tests done with depth integrating samplers, so no spatial or depth variability correction factor was applied. In total, 353 water samples were taken during the monitoring period (hydrological year 2011–2012), of which 275 were used for turbidimeter calibration and 78 for chemical analyses (i.e., 11 for Q_5, 25 for Q_{50} and 42 for Q_{95}; Table 1). The number of samples taken for the chemical analyses varied proportionally between the different flow conditions, so it was assumed that the highest and most representative SSC (and hence total amounts of C and N) would be reached during floods rather than during baseflows.

Table 1.

Water samples collected at the three monitoring sections during the study period (2011-2012).

Site	Chemistry[a]	Q_5[b]	Q_{50}[c]	Q_{95}[d]	Calibration[e]	Total	SSC_{max}[f]	SSC_{min}[g]	SSC_{mean}[h]	Q_{max}[i]	Q_{min}[j]	Q_{mean}[k]	FQ[l]
ESE	33	3	3	27	134	167	17.200	0.003	1.227	194.8	1.2	41.5	97
ISA	40	3	22	15	101	141	123.113	0.004	9.653	39.3	1.7	10.8	35
BAR	5	5	-	-	40	45	0.020	0.001	0.007	0.3	0.3	0.3	100
Total	78	11	25	42	275	353	-	-	-	-	-	-	-

[a] *Samples taken for chemical determinations*
[b] *Samples taken during low-flow for chemical determinations (see text for details)*
[c] *Samples taken during medium-flow for chemical determinations (see text for details)*
[d] *Samples taken during high-flow for chemical determinations (see text for details)*
[e] *Samples taken for turbidimeters calibration*
[f] *Maximum SSC of all the samples taken*
[g] *Minimum SSC of all the samples taken*
[h] *Mean SSC of all the samples taken*
[i] *Maximum discharge sampled*
[j] *Minimum discharge sampled*
[k] *Mean discharge sampled*
[l] *percentage of time in the flow duration curves of the study period covered by the discharges in which sampling was carried out (see Figure 4 for more details)*

3.2. Determination of suspended sediment. C and N analysis

Water samples were processed differently according to the objective for which they were taken. Water samples which were going to be used just for turbidimeter calibration were processed in the laboratory as follows. Samples were either filtered by means of 1.2 µm cellulose and glass microfibre filters (samples with a small amount of sediment) or decanted (samples with a large amount of sediment) and then dried in an oven for 24 h at a constant 60 °C. Filters and decanted samples were subsequently weighted to determine *SSC* (g l^{-1}). Once the samples were processed, it was possible to establish an individual rating curve for each turbidimeter between pair values of *SSC* and turbidity (after records were reviewed, corrected and validated; see details of the method in López-Tarazón et al., 2009). In the case of ESE, the statistically significant rating curve yielding the highest coefficient of determination was $SSC = (0.1736 \times TU^2) + (0.781 \times TU)$ (r^2 =0.91, $p < 0.001$), while in the case of BAR it was $SSC = (0.0012 \times TU) - 0.0091$ ($r^2 = 0.98$, $p < 0.001$). Finally, the rating curve used in ISA was *SSC* =

(0.0526 × TU^2) + (2.489 × TU)(r^2 = 0.97, $p < 0.001$), an improved version of that published in López-Tarazón et al. (2009) built by adding more pairs of *SSC*-turbidity values to those used for the original curve. In all cases, TU represents the units in which each single device measures turbidity.

Water samples which were taken for C and N analysis were cold stored in fridges until they were analysed in the lab. Samples were filtered through 500 °C pre-ashed and pre-weighed 0.7 μm glass microfibre filters and kept refrigerated again. Then, C and N concentrations were determined using an elemental Carlo-Erba CN autoanalyser. Total C (hereafter TC) was measured directly in one aliquot without any previous treatment, while OC was measured in another aliquot of sediment previously treated with HCl to remove carbonates. Finally, IC was estimated by the difference between TC and OC.

3.3. Load calculations

Once a continuous *Q* and *SSC* (i.e. transformed from turbidity) record was obtained for each measuring point at a 15-min time resolution (Fig. 2), suspended sediment load (hereafter *SSL*) was simply calculated by multiplying *Q* and *SSC* for each 15-min interval, finally adding all the (singular) values together to obtain the total sediment load transported through each site along the study period. Due to the high degree of accuracy obtained by the *h/Q* and *SSC*/turbidity rating curves, discharge and suspended sediment load uncertainty was considered to be negligible. C and N loads were calculated similarly; an average value of TN, TC, IC and OC (in percentage) was obtained for each site and each flow condition (Table 2). Then, this percentage was applied to the *SSL* calculated for each flow condition and at each 15-min interval which were later added to obtain the annual loads. Uncertainties with the TN, TC, IC and OC loads were calculated by considering the standard deviation (SD) of the analysed samples for the different flow conditions, then applying the same procedure aforementioned to obtain the annual loads. The uncertainty for the final TN, TC, IC and OC loads was defined as two times their SD to obtain the 95% confidence limits (CI) (Némery et al., 2013). Finally, temporal dynamics were also assessed for ESE and ISA by means of duration curves for each of the studied variables (i.e., runoff, SSL, TN, TC, OC and IC). Curves were constructed by plotting the accumulated percentage of variables, as Y coordinates, and the percentage of time that each variable range was equalled or exceeded, as X coordinates. Sediment time concentration was not assessed in the case of BAR as discharge did not change significantly during the study period.

4. RESULTS AND DISCUSSION

4.1. Flow discharge and suspended sediment load

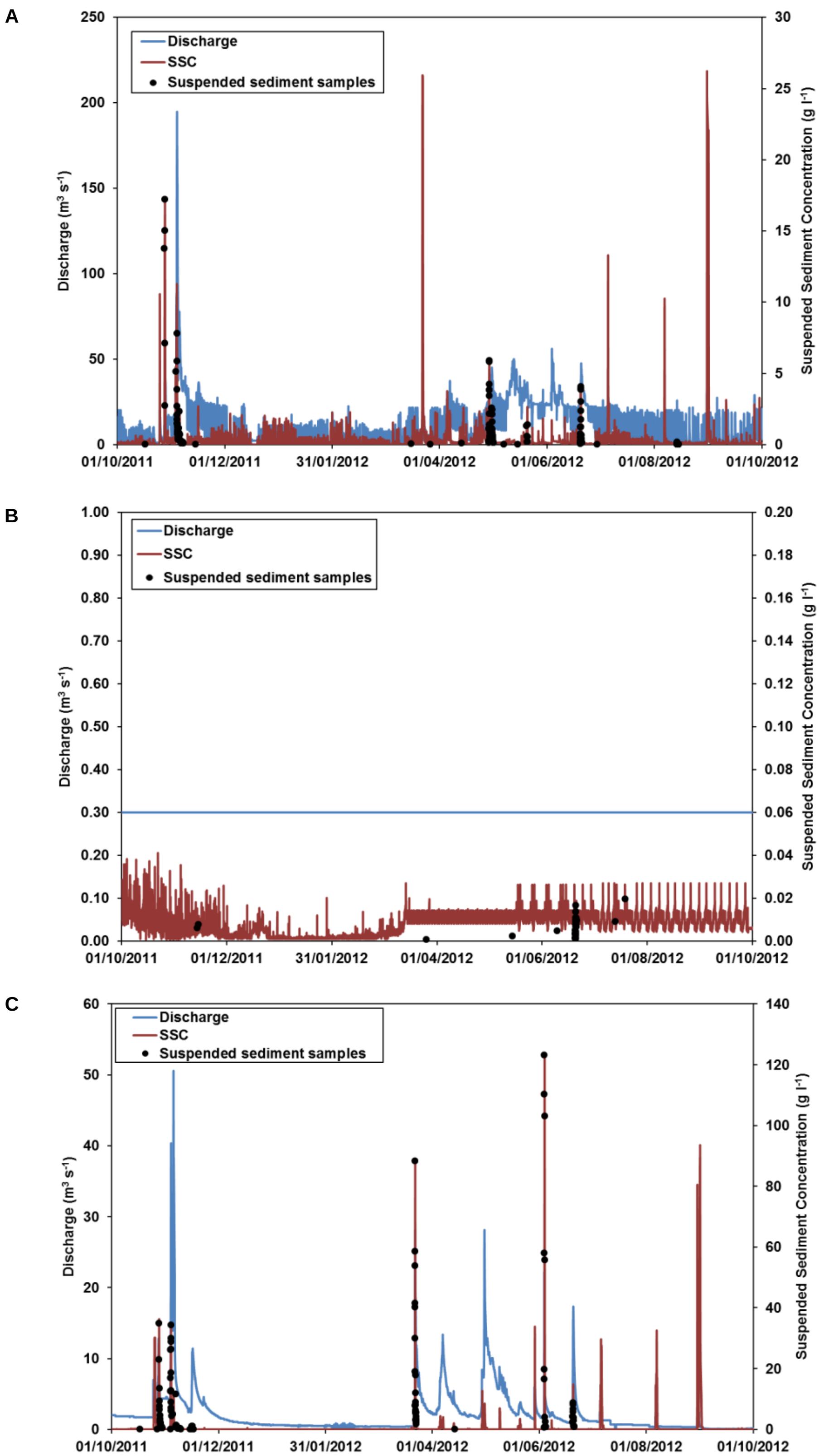

Fig. 2. *Discharge and suspended sediment concentration recorded together with the water samples taken at (A) ESE, (B) BAR and (C) ISA along the study period.*

Fig. 2 represents the discharge and the suspended sediment concentration recorded at the three study sites during the study period. In this figure, the distinct hydro-sedimentological behaviour between sites becomes evident. The study year is dry to very dry from the hydrological point of view (Table 3). In the case of ESE, annual runoff (hereafter *AR*) was 342 hm^3, a value that is about half the historical average (600 hm^3 for the period 1949–2010), while in the case of ISA, the 66 hm^3 registered represented around 1/3 of the historical mean (177 hm^3 for the period 1949–2010). These values result from the fact that the dam strategy was exclusively focused in retaining water, hence the amount of water which was released by the dam and circulated downstream in the river was very much reduced, accounting for just 1/8 of the historical average (9 hm^3 during the study year, in comparison to the 69 hm^3 of the period 1991–2012).

Table 2.
Average results of suspended sediment concentration (*SSC*) and total Nitrogen (*TN*), total, inorganic and organic Carbon (*TN*, *IC* and *OC* respectively) in both concentration (mg l^{-1}) and percentage of weight over sediment dry weight (%), together with the *C/N* ratio (i.e. ratio between *TN* and *OC*) for all the samples analysed at the three study sites and at all flow conditions. Standard deviations (i.e. *SD*) of the analysed components are also shown. The *SD* of *IC* has not been calculated as it was obtained by subtracting *OC* from *TC*.

Site	Flow condition	SSC (g l^{-1})	TN (mg l^{-1})	SD (%)	TN (%)	TC (mg l^{-1})	SD (%)	TC (%)
ESE	*Low-flow*	4.534	0.003	0.02	0.05	0.555	0.21	8.19
	Medium-flow	0.007	6.167	0.15	0.09	443.216	0.53	5.56
	High-flow	8.230	3.160	0.11	0.07	239.981	0.78	5.53
	Mean	4.248	3.380	0.09	0.07	252.831	0.51	5.74
ISA	*Low-flow*	0.011	0.008	0.03	0.08	1.680	0.18	15.79
	Medium-flow	9.880	7.899	0.09	0.06	466.155	0.87	5.57
	High-flow	17.769	13.194	0.13	0.08	937.530	1.21	5.40
	Mean	12.904	9.983	0.08	0.07	655.165	0.75	6.17
BAR	*Low-flow*	0.004	0.004	0.07	0.13	0.331	0.11	11.48
Mean		7.652	6.124	0.086	0.08	397.452	0.495	6.81
CV[a]		74.984	83.653	N/A	247.55	76.763	N/A	171.23

[a] *Coefficient of variation (%)*

Site	Flow condition	TC (%)	IC (mg l^{-1})	IC (%)	OC (mg l^{-1})	SD (%)	OC (%)	C/N
ESE	*Low-flow*	8.19	0.253	3.73	0.302	0.05	4.46	88.36
	Medium-flow	5.56	396.266	4.86	46.951	0.95	0.70	8.13
	High-flow	5.53	217.926	4.77	22.055	1.16	0.76	13.30
	Mean	5.74	228.619	4.70	24.212	0.72	1.03	18.28
ISA	*Low-flow*	15.79	1.022	9.60	0.658	0.11	6.19	77.96
	Medium-flow	5.57	424.749	4.67	48.307	0.65	1.35	10.99
	High-flow	5.40	872.074	4.94	76.365	0.94	0.57	6.93
	Mean	6.17	605.252	5.13	57.592	0.57	1.37	14.54
BAR	*Low-flow*	11.48	0.093	2.07	0.238	0.08	9.41	68.61
Mean		6.81	365.191	4.50	34.343	0.56	2.52	22.07
CV[a]		171.23	75.567	313.48	70.062	N/A	55.24	73.09

[a] *Coefficient of variation (%)*

Fig. 2 also shows the important role that hydropeaks exerted on the discharge recorded at ESE, generating flood events of different magnitude (i.e. Q_{max} ranging from 1 to around 20 m^3 s^{-1}) on a daily basis, hence altering the flow regime of the river notably. The importance of hydropeaks can be seen more clearly if the hydrograph registered at ESE is compared with that in ISA (Fig. 2A and C). Both are similar concerning the frequency (not the magnitude) of the flood events as they are nested catchments which share headwaters, but their flow pattern is different. Some floods are easily identified in ISA, whereas it is very difficult to differentiate natural floods from daily hydropeaks in the case of ESE. Nevertheless, a total of 11 natural flood events were identified in ESE with Q_{max} ranging from 18 to 195 $m^3 s^{-1}$ (discharges corresponding to a return period of 0.4 and 1.3 years respectively), while 14 floods were observed in ISA with Q_{max} varying between 1.5 and 51 $m^3 s^{-1}$ (discharges corresponding to a return period of 0.5 and 1.1 years respectively). This proves that the hydrological response at both basins was accordingly similar to the observed return periods of the floods but of low magnitude. Further downstream, discharges were totally stable at around 0.3 $m^3 s^{-1}$ in BAR along the study period (Fig. 2b) as no flushing operation was executed from the dam and just the water passing through the wall via infiltration fed the river.

Table 3.
Seasonal and annual results of suspended sediment load (SSL), specific sediment yield (SSY), mean and maximum suspended sediment concentration (SSC_{mean} and SSC_{max} respectively), runoff (WY), total Nitrogen and specific total Nitrogen (TN and STN), total Carbon and specific total Carbon (TC and STC), inorganic Carbon and specific inorganic Carbon (IC and SIC) and organic Carbon and specific organic Carbon (OC and SOC) obtained at the three monitoring sites. TN, TC and OC loads are given with 95% confidence intervals between brackets (see text for calculation); confidence intervals for IC have not been calculated as it was obtained by subtracting OC from TC.

Site	Season	SSL (t)	SSY (t km^{-2})	SSC_{mean} (g l^{-1})	SSC_{max} (g l^{-1})	WY (hm^3)	TN (t)	STN (t km^{-2})
ESE	*Autumn*	85,002	-	0.26	17.20	89	63*(0.013)*	-
	Winter	12,466	-	0.22	25.94	33	11*(0.001)*	-
	Spring	43,374	-	0.25	5.90	166	39*(0.008)*	-
	Summer	25,622	-	0.39	26.03	55	22*(0.004)*	-
	Total	166,464	157	0.28	26.03	342	134*(0.027)*	0.13
ISA	*Autumn*	56,782	-	0.57	36.08	24	41*(0.008)*	-
	Winter	29,946	-	0.19	88.36	8	24*(0.005)*	-
	Spring	33,983	-	0.49	123.11	30	20*(0.004)*	-
	Summer	6,127	-	1.01	92.92	4	4*(0.001)*	-
	Total	126,838	285	0.57	123.11	66	88*(0.018)*	0.20
BAR	*Autumn*	10	-	0.006	0.041	2	0.01*(0.00)*	-
	Winter	6	-	0.004	0.027	2	0.01*(0.00)*	-
	Spring	19	-	0.011	0.026	2	0.02*(0.00)*	-
	Summer	17	-	0.010	0.027	2	0.01*(0.00)*	-
	Total	52	0.03	0.008	0.041	9	0.04*(0.00)*	0.00

Site	Season	TC (t)	STC (t km^{-2})	IC (t)	SIC (t km^{-2})	OC (t)	SOC (t km^{-2})
ESE	*Autumn*	4,731*(39)*	-	4,064	-	667*(2.4)*	-
	Winter	718*(6)*	-	595	-	123*(0.4)*	-
	Spring	2,418*(20)*	-	2,103	-	315*(1.1)*	-
	Summer	1,520*(12)*	-	1,203	-	317*(1.1)*	-
	Total	9,387*(77)*	8.82	7,965	7.49	1,422*(5.1)*	1.34
ISA	*Autumn*	3,125*(23)*	-	2,764	-	361*(1.1)*	-
	Winter	1,621*(12)*	-	1,477	-	144*(0.4)*	-
	Spring	1,888*(14)*	-	1,612	-	276*(0.9)*	-
	Summer	378*(3)*	-	314	-	64*(0.2)*	-
	Total	7,012*(52)*	15.76	6,167	13.86	845*(2.6)*	1.90
BAR	*Autumn*	1.1*(0.01)*	-	0.2	-	0.9*(0.01)*	-
	Winter	0.7*(0.01)*	-	0.1	-	0.6*(0.01)*	-
	Spring	2.2*(0.02)*	-	0.4	-	1.8*(0.03)*	-
	Summer	1.9*(0.01)*	-	0.4	-	1.6*(0.03)*	-
	Total	6.0*(0.05)*	0.00	1.1	0.00	4.9*(0.08)*	0.00

At the seasonal scale, the hydrological pattern was similar both in ESE and ISA, and to that previously reported by different authors (i.e. López-Tarazón et al., 2012; Palazón and Navas, 2014). Spring was the season yielding the largest amount of water (i.e. 166 and 30 hm^3, respectively) followed by autumn (89 and 24 hm^3), although the contribution of *Q* in autumn was more important in ISA (i.e. it represented 37% of the total *AR*) than in ESE (i.e. 26% of the *AR*). However, there is an important difference concerning dry seasons; in the case of ESE winter accounted for 10% of *AR* (i.e. 33

hm^3), while summer represented just the 6% of the *AR* (i.e. 4 hm^3) in ISA (Table 3; Fig. 3). This behaviour is likely to be explained by the fact that despite both basins having a nivo-pluvial hydrological regime (i.e. spring is the wettest season due to snowmelt), precipitation in the form of snowfall is more frequent in the Ésera catchment than in the Isábena, hence reducing runoff in winter in the case of the former.

The importance of the high *SSC* that is habitually transported, even during baseflows, has been extensively documented in the case of the River Isábena (i.e. López-Tarazón et al., 2009, 2012; Piqué et al., 2014), and can be extended to its neighbouring Ésera river. Mean average *SSC* of 0.28 and 0.57 g l^{-1} (with maximum values of up to 26 and 123 g l^{-1}) were recorded at ESE and ISA respectively during the study period (Table 3). Such *SSC* led to suspended sediment loads of 166,464 t in ESE and 126,838 t in ISA, representing an annual specific sediment yield (i.e. hereafter *SSY*) of 157 and 285 t km^{-2} respectively. Sediment yields appeared to be quite similar despite the huge differences observed in runoff (i.e. 342 hm^3 in ESE for just 66 hm^3 in ISA) (Table 3). This feature can be mainly attributed to the specific area that is covered by badlands at both areas and their connectivity with the main stream (i.e. a more important fact in the case of the Isábena rather than in the case of the Ésera), together with the importance that the in-channel fine sediment storage has over the sediment budget. In the specific case of the Isábena, the existence of an annual sedimentary cycle (i.e. the residence time of the sediment within the catchment is of the order of 1 year) has been established. Therefore, fine sediment is produced in badlands during winter (mainly by means of freezing/thawing processes), transferred to the main channel (and surrounding areas) during spring, stored in the river during summer and, finally, exported out of the basin by the autumn floods (or as soon as an event competent enough arises) hence delivering huge amounts of sediment for not such remarkable discharges (i.e. Piqué et al., 2014). Particularly, in-channel fine sediment accumulations control the river's load during some seasons, being for instance responsible for up to 55% of the total sediment transport in winter (López-Tarazón et al., 2011). In-channel accumulations have been examined in the Isábena but, despite not yet having been analysed for the entire Ésera catchment, field evidence suggests that fine sediment storage is an important factor there too. However, we believe that they might not be as important as in the case of the Isábena for two main reasons: i) badlands are directly connected with the fluvial network at both the Ésera and the Isábena but, while connections are established with small tributaries which are usually dried up in the former, they are directly established with the main tributaries which continuously deliver water into the main stream in the latter; ii) flux connectivity is also altered in the case of the Ésera due to the several small weirs which are spread along the main stream; these weirs likely retain and store a large part of the sediments which are delivered by the badlands, making the sediment unavailable (unless an extreme or catastrophic flood happens). This issue does not happen at all in the case of the river Isábena, as it is completely unaltered (i.e. no man-made hydraulic construction at all which could alter the river fluxes can be found in the whole catchment), so there is no element that could disconnect the fine sediments from the fluvial network and hence prevent sediment transport. Despite the high values observed, *SSL* in the study period can be considered as very low for the study basins, amounting to less than half the long-term average, which is 266,000 t in the case of the Isábena (600 t km^{-2} yr^{-1}; López-Tarazón and Batalla, 2014) and around 560,000 t in the case of the Ésera (i.e. 530 t km^{-2} yr^{-1}; Palazón and Navas, 2014). Nonetheless, these figures can still be considered high, based on the World River classification developed by Meybeck et al. (2003). Finally, only 52 t circulated through BAR, and hence *SSY* (if applicable) was almost negligible (i.e. 0.03 t km^{-2}).

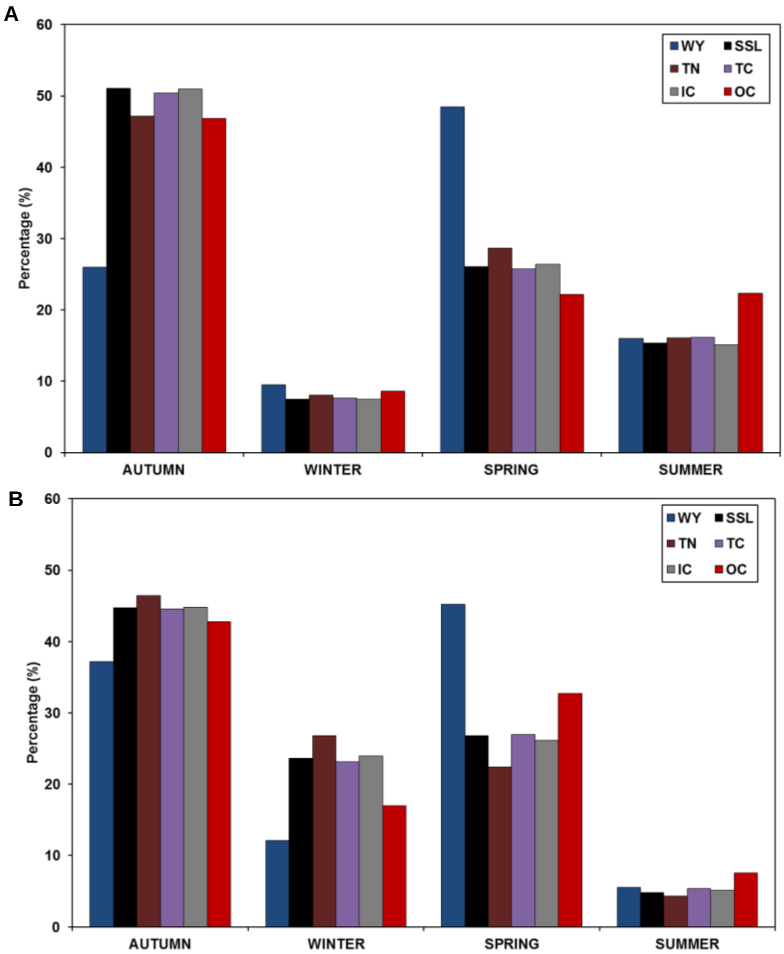

Fig. 3. *Seasonal distribution (percentage over the total) of the suspended sediment load (SSL), runoff (WY), total Nitrogen (TN) and total, inorganic and organic Carbon (TC, IC and OC respectively) at (A) ESE and (B) ISA for the study period.*

At the seasonal scale, the highest SSL do not correspond with the highest AR; at both ESE and ISA, spring was the wettest season while autumn was the season transporting the highest SSL (Table 3). This issue can be explained because of two different facts: i) autumn, despite not being the wettest season, was the season accounting for the highest number of flood events, hence it was the season with the highest transport capacity; ii) in-channel sediment storage was especially remarkable in the case of autumn, as large amounts of fine sediment had already accumulated during the previous spring and summer seasons (before the beginning of the present work study period) thus they were extremely dry and no flood was recorded during these seasons. Therefore, high fine-sediment storage within river channels followed by a period of high flows generated large amounts of SSL for such an unelevated AR (as aforementioned).

Runoff and SSL show distinct duration patterns for ESE and ISA throughout the study period, with runoff being more constant than sediment through time (Fig. 4). Frequency curves were not calculated for BAR due to the absolutely stable Q recorded during the whole study year (i.e. any change in Q was hardly ever observed, nor did any flood occur). Discharges smaller than the long-term mean flow (i.e. 18.5 $m^3 s^{-1}$ in ESE and 4.1 $m^3 s^{-1}$ in ISA) are responsible for ca. 25% and 8% of the SSL respectively, while 50% of the SSL is transported during flows greater than 34 and 22 $m^3 s^{-1}$ for ESE and ISA. These discharges (e.g. three and eleven times higher than the mean discharge of the study period) are equalled or exceeded at 3% of the time in ESE and just 0.5% in ISA (Fig. 4). Differences in the SSL patterns can be seen better in the case of the 90th percentile of the load that is transported by discharges equalled or exceeded 80% of the time in ESE but just 47% of the time in ISA (Fig. 4). A breakpoint can be visually established at around 70% of the load for ESE and 90% for ISA, above which sediment transport becomes more constant, both corresponding to a duration of around 10% of the time.

Finally, the behaviour of the Isábena coincides with that reported for similar-sized Mediterranean basins, in which 90% of the suspended load is transported 10% of the time (Batalla et al., 1995; Rovira and Batalla, 2006). However, it clearly departs from previous results obtained in the same catchment (i.e. López-Tarazón et al., 2009; López-Tarazón and Batalla, 2014) in which 90% of the SSL was usually transported during 30% of the time. Such deviation can be attributed to the unusual drought that occurred during the study year. It is worth noting though that the Ésera behaved as the Isábena does in a regular year (i.e. 90% of the SSL was transported the 30% of the time). This fact illustrates that floods are responsible for most of the SSL (as expected) but that the continuous availability of sediment (whether it comes straight from the badlands or from the different storage areas within the drainage network, e.g. channel-bed) results in a more constant sediment transport. Therefore, although sediment yield is mainly dependent upon floods, base flows, small floods and even daily flow-fluctuations can play an important role in sediment export.

4.2. C and N: Loads and temporal dynamics

C (i.e. TC, IC and OC) and N (i.e. TN) loads at the three study sites during the study period are summarized in Table 3 and represented in Fig. 3; temporal dynamics through the evaluation of the frequency curves (which have been derived for ESE and ISA only due to the stable Q conditions registered at BAR) are plotted in Fig. 4. At the annual scale, TC load is clearly the dominant process in both basins, accounting for almost two orders of magnitude more than TN i.e. ESE yielded 9387 ± 77 t of TC, while just 134 ± 0.03 t of TN; ISA transported 7012 ± 52 t of TC and just 88 ± 0.02 t of TN; finally, BAR only flushed down the dam 6 ± 0.05 t of TC and 0.04 ± 0.00 t of TN (Table 3). In the case of TC the relation between IC and OC was similar in ESE and ISA, with IC representing 85% of the TC; however, this relationship was exactly the opposite in the case of BAR (i.e. OC represented around 85% of TC). This feature can be attributed to two facts: i) relatively low values of OC in the suspended sediment (0.78% of the incoming matter), compared to that observed for the surface sediments of the reservoir (up to 3.5% sediment composition; López et al., this volume), are likely caused by a combination of different factors mainly related to the long transport distances of the sediment from the sources which favour a continuous remobilisation, and hence facilitate aggregate breakdown and OC mineralisation; ii) the high percentage of OC downstream of the dam is probably due to in situ formation of new OC either in the reservoir or in the river reach between the dam and BAR, due to the remarkably low and stable Q conditions (i.e. even experiencing no disturbance for years) (e.g. Einsele et al., 2001; Amegashie et al., 2011).

Total amounts of TN and TC (and IC and OC) are lower than usual due to the dryness of the study year and the relatively low SSL which was transported at the three measuring points. Despite this fact, values perform within the same order of magnitude if compared in specific terms (i.e. in relation to the catchment size; Table 3) with other studies, even though they were carried out in different climatic and geographical locations. For example, Némery et al. (2013) in the upper mountainous part (i.e. 5570 km^2) of the highly turbid River Isère, and Marttila and Kløve (2014) at the greatly affected by fine-grained in-channel sediment storage River Sanginjoki (i.e. 400 km^2), obtained TC loads of 30 and 18 t km^2 yr^{-1}, respectively. In contrast, the present study yielded higher TN and OC than the results of Xu (2013) in an area of 3923 km^2 of the River Atchafalaya, which has been significantly engineered for flood-control, yielding a specific OC and TN of 0.29 and 0.04 t km^2 respectively. This issue can be attributed to the similarity in terms of lithology/geology, sediment sources and cycles of sediment transport, in-channel deposition and storage and remobilisation of the Ésera and Isábena rivers (i.e. López-Tarazón et al., 2011; Piqué et al., 2014) with the Isère and Sanginjoki rivers. The high erosion rates of these rivers lead to relatively high values of TC (mostly inorganic) derived from sedimentary and carbonate rock weathering and erosion (Aucour et al., 1999) but relatively low values of OC, as observed in highly erodible catchments (Kao and Liu, 1997; Hilton et al., 2008) or in sedimentary rock catchments (Meybeck et al., 2005).

At the seasonal scale, TN, TC and IC followed a similar pattern to that of SSL. Autumn was the season with the highest transport in both ESE and ISA, while seasons transporting the lowest amounts were winter in ESE and summer in ISA (Fig. 3). However, the pattern was different for OC, increasing its importance in relation to the load in seasons in which the autochthonous primary production is likely to be the highest (i.e. spring and summer in Mediterranean river ecosystems, e.g. Romaní et al., 2013). This behaviour can be seen even better in Fig. 4, where TC and IC follow the SSL pattern, but TN performs differently at both sites being more constant than SSL in ESE and more variable in ISA; OC is transported more constantly through time than SSL at both sites, and the difference is remarkable in the case of ISA (i.e. 50% of the SSL was transported 0.6% of the time, and 50% of the OC 3% of the time; 90% of the SSL was transported around 10% of the time while 90% of the OC 70% of the time). These results highlight once again the role of low flows in relation to floods as the main process transporting OC.

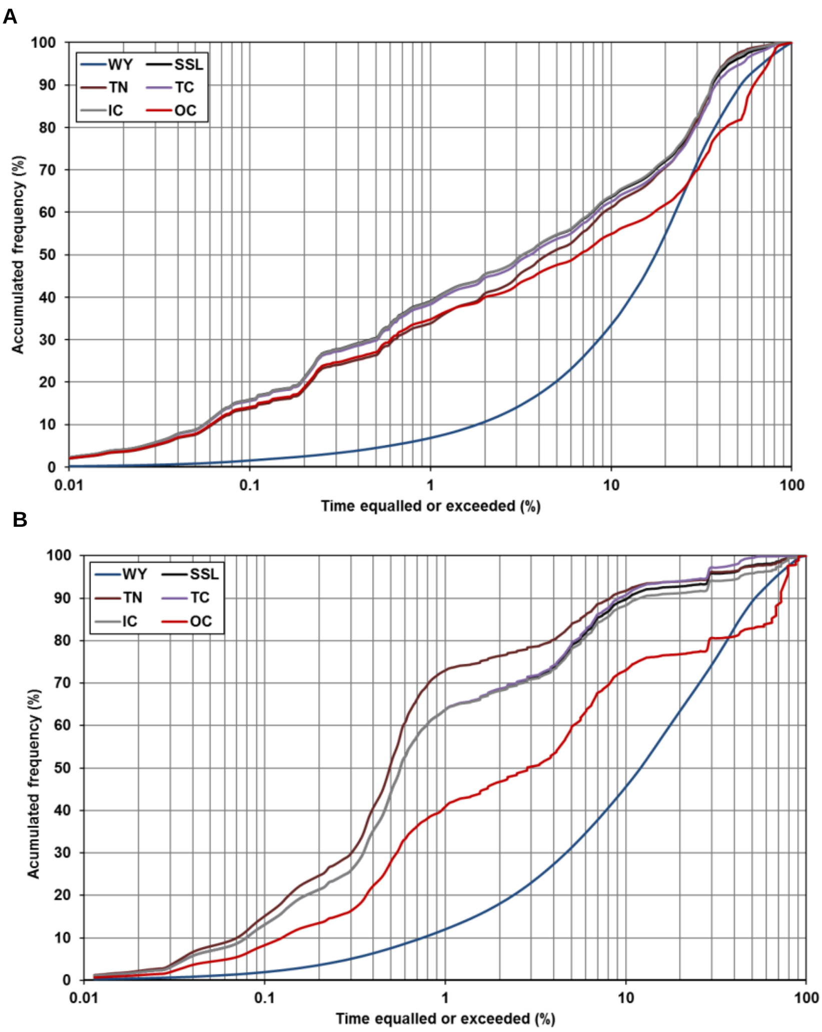

Fig. 4. *Suspended sediment load (SSL), runoff (WY), total Nitrogen (TN) and total, inorganic and organic Carbon (TN, IC and OC respectively) duration curves of (A) ESE and (B) ISA for the study period.*

4.3. Relation between C, N and suspended sediment

The main results regarding the chemical analyses of the suspended sediment samples taken at the three study sites for all flow conditions are presented in Table 2, with the relationship between them and SSC plotted in Fig. 5 (BAR is not presented in Fig. 5 as it has been analysed for normal-flows only). The highest concentrations of TN, TC, IC and OC (in mg l^{-1}) are always transported by medium to high flows, a fact that is related to the largest SSC usually reached during such flow conditions. However, if the composition (i.e. the percentage of OC, TC and TN relative to the dry weight of the sediment samples) of the transported material during medium-high flows is compared with that transported during low-flows it can be observed that the material transported by the former discharges was enriched in IC but depleted in TN, TC and OC (Fig. 5).

The highest C/N ratios (i.e. 88, 69 and 78 for ESE, BAR and ISA, respectively) were observed during low-flows and the smallest ratios (i.e. <7) were obtained for medium to high-flows (Table 2; Fig. 6). These facts suggest different processes of loss and gain of OC or TN in relation to the different sediment transport and flow conditions. The high values of C/N and OC observed for low-flow conditions may indicate either an export of fossil OC (e.g. Smith et al., 2013) or the presence of biogenic sources dominated by terrestrial or even non-vascular aquatic plants (e.g. Goñi et al., 2013). Alternatively, the low C/N ratios observed for medium-high flow conditions (those transporting the highest SSC and hence SSL) could indicate that only such type is capable of transporting fresh sediments (enriched OC) directly from the sources (which in our study cases are the badlands located mainly in the middle part of the basins; Fig. 1). However, due to the long distances that these fresh sediments have to cover until reaching the outlet (and the time needed too), the OC could be partially mineralised and hence reduced, meaning that the only materials rich in OC draining into the reservoir should be the fine organic microaggregates or single particles (i.e. Boix-Fayos et al., 2015) which have been just recently formed by primary producers.

In any case, the interpretation of C/N ratios has to be carefully considered given the complexity of the N behaviour along the fluvial path (e.g. Robertson and Groffman, 2007; Wang et al., 2010). Nitrification and denitrification processes are dependent, for example, on the drying and rewetting cycles of sediments (Gómez et al., 2012; Arce et al., 2013), a fact that usually takes place in both rivers (especially in the Isábena) due to the large amounts of fine sediments that are deposited in the channel bed and the adjacent floodplains following the continuous cycle of deposition, drying, rewetting and remobilisation at the annual (or even seasonal) time scale (i.e. López-Tarazón et al., 2011; Piqué et al., 2014). Therefore, cycles of nitrification/denitrification could contribute directly to the very low N concentrations observed in the suspended material, a fact that has to be analysed in detail in further studies.

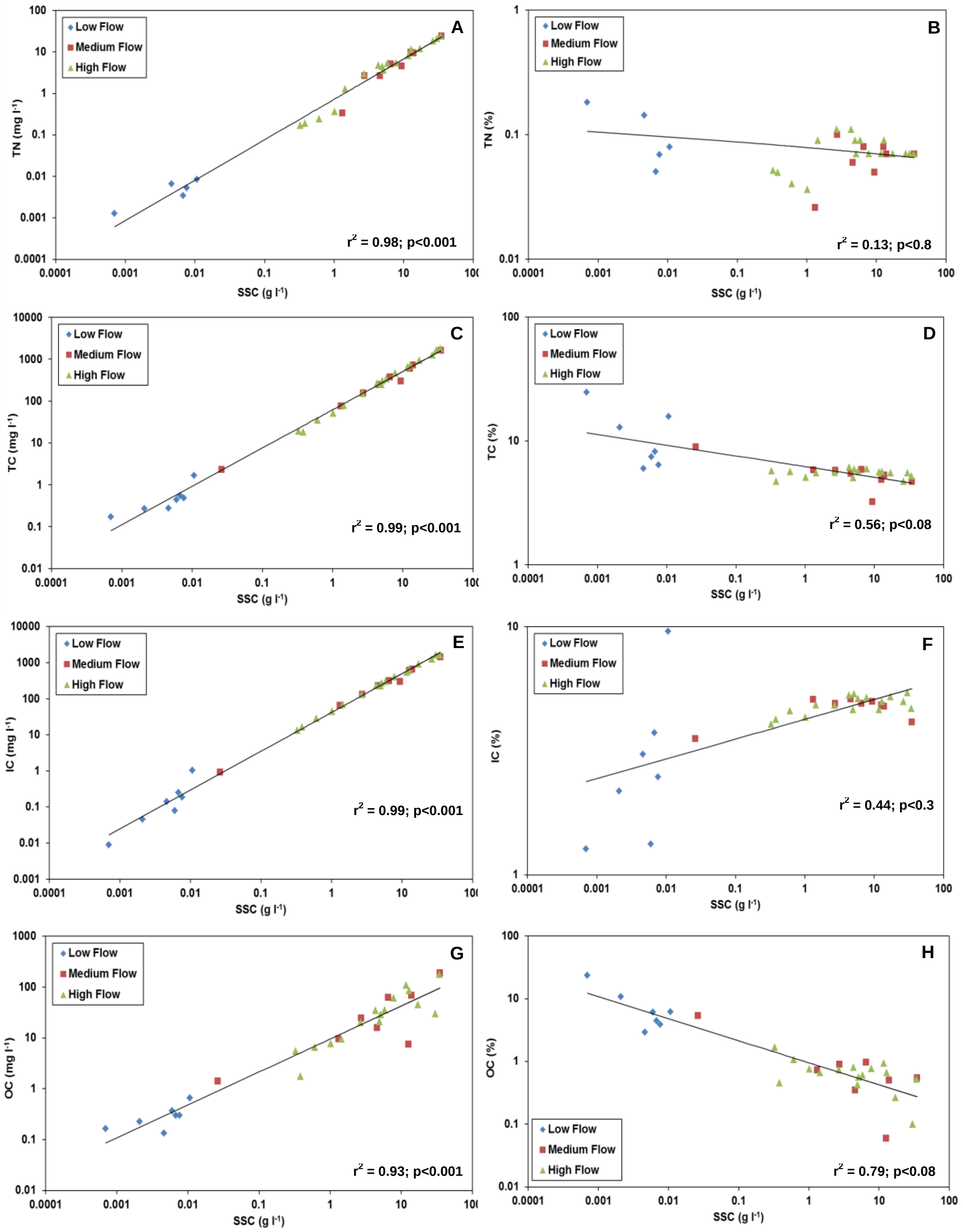

Fig. 5. *Relations obtained between suspended sediment concentration and total Nitrogen (TN), total, inorganic and organic Carbon (TN, IC and OC respectively) in concentration (mg l^{-1}; A, C, E, and G) and percentage values over dry weight (B, D, F, and H) values for all the samples analysed at the three study sites and at all flow conditions. Each figure includes the value of the obtained correlation and the p-value for which the correlation is significant.*

4.4. Impacts of the reservoir on suspended sediment, C and N fluxes

The results illustrate the important effect that the Barasona Reservoir exerts on the rivers Ésera and Isábena. Water, sediment and the associated Carbon and Nitrogen fluxes are reduced, together with the frequency and magnitude of floods, when comparing the fluxes inflowing into the reservoir with those outflowing through the dam (Table 3). Significant quantities of sediment are transported by both Ésera and Isábena rivers, nearly all of which accumulates in the reservoir, as the sediment that flows through the dam down the river is almost negligible (Table 3; Fig. 2). The amount of C and N that is deposited (and has been deposited throughout time) in the reservoir along with the fine sediment is also significant. If we consider the dry study year (without taking into account the different processes for which C and N could vary, e.g. atmospheric loss, natural enrichment or depletion), a total of 293,250 t of suspended sediment were deposited into the Barasona Reservoir, from which 16,393 ± 129 t were TC (i.e. 2262 ± 8 t of OC) and 222 ± 0.05 t were TN. These values are remarkable for a reservoir of such size but are small, of course, if put in a wider global context (e.g. the total river annual export can be estimated at around 200×10^6 t of OC and 30×10^6 t of TN; Beusen et al., 2005). In the long-term and both assuming that the dry density of the sediment is 1.52 g cm^{-3} (Mamede, 2008) and that the amount of sediment that is currently stored in the reservoir is, at least, 30 hm^3 (Mamede, 2008), a total of 45.6×10^6 t of sediment should be estimated to be deposited in Barasona. This figure could be roughly transformed into a total of ca. 2.6×10^6 t of TC (i.e. 360,000 t of OC) and 35,000 t of TN since the reservoir was constructed. However, values of OC accumulation in the reservoir have to be considered carefully. López et al. (this volume) have reported that oxygen consumption by the sediments deposited in the Barasona Reservoir is quite high (similar to that observed by some tropical rivers; Cardoso et al., 2014) hence discriminating whether it is released to the atmosphere as CO_2 or remains in dissolved form in the water requires further research.

Previous figures have represented a rough estimation of the long-term accumulations of C and N, and values could be likely underestimated, especially considering the dryness of the study year and the low sediment inputs to the reservoir in comparison to regular hydrological years. Overall, the amount of TN is low in relation to the global context (i.e. caused by the lack of diffuse agricultural pollution and the almost pristine conditions of both basins in terms of agricultural areas) whereas OC is remarkable, especially concerning the different processes which likely occur within the reservoir through time, likely leading to its increase. As observed by López et al. (this volume) OC enrichment of the Barasona sediments cannot be attributed to the sedimentation of autochthonous primary production because the concentrations of chlorophyll-a and phytoplankton biomass were very low in the surface sediments deposited in the reservoir. Moreover, the high values observed for the ratio C/N in the reservoir deposited sediments (ca. 45–55, far above the characteristic 4–10 of phytoplankton; Meyers and Ishiwatari, 1993), together with the similar values obtained for TN at both the deposited sediments and the sediment fluxes (< 0.1%) indicate that allochthonous matter is probably the main source of OC in the Barasona stored sediment. Moreover, in this kind of Mediterranean river ecosystems, OC decomposition rates and dynamics can be different at the seasonal scale, depending on whether the inputs of organic matter are mainly allochthonous (i.e. higher inputs in autumn) or autochthonous (i.e. the highest primary production), so a more detailed determination of the organic matter inputs should be carried out. In addition, OC inputs, decomposition and dynamics can also be influenced by river hydrodynamics (e.g. Cabezas and Comín, 2010; Devesa-Rey and Barral, 2012) which, in turn, are fundamentally altered by the presence of the dam. This way, frequent large fluctuations in water level, can also produce resuspension and mixing of the surface sediment layer with the fresh sediment recently deposited (Nagid et al., 2001; Håkanson, 2005; Shotbolt et al., 2005), resulting in an apparent OC enrichment and a homogenization of OC content along and across the reservoir (López et al., this volume).

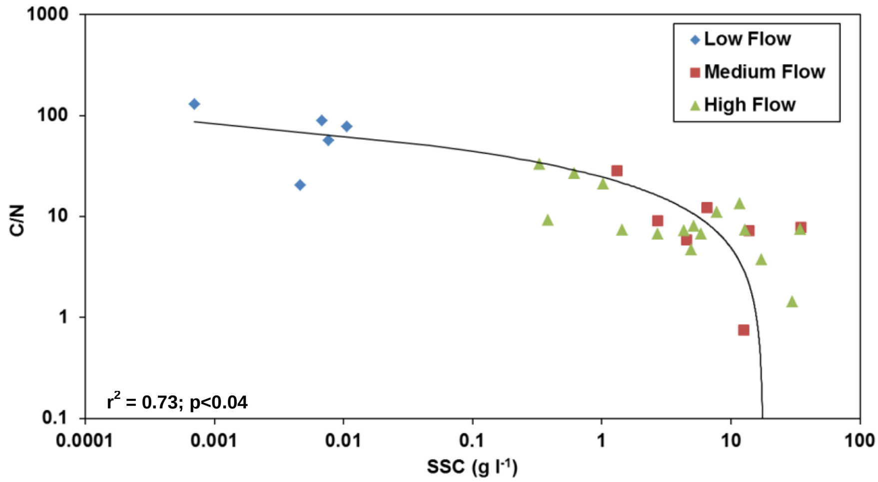

Fig. 6. *Relation obtained between suspended sediment concentration and the C/N ration (i.e. ration between TN and OC) for all the samples analysed at the three study sites and at all flow conditions.*

5. FINAL REMARKS

The present work has reported on the suspended sediment, carbon and nitrogen transport in a regulated Pyrenean river (the Ésera and its main tributary, the Isábena), and has examined the effect of the Barasona Reservoir on such fluxes. We compared the different fluxes that inflow into the reservoir with those that outflow, remarking that nearly all the flow and particulate matter are retained in Barasona, as no flushing operation was carried out in the dam during the study period. In addition, the large amount of fine-sediment that has been historically accumulated in the reservoir (chronically threatening its storage capacity and hence its irrigation capacity) have led to a very remarkable deposition of C too (despite the low percentages of C which have been quantified for the incoming sediment flux), especially if the relatively small size of the reservoir is taken into account. However, the higher percentage of C observed in the reservoir's surface sediments (López et al., this volume), indicates that different factors could have led to an increase in the deposited C (especially the OC) in the reservoir, so that the impact of the reservoir on C transport (and associated biogeochemical cycles) could be even more remarkable than stated here.

This work, together with the work by López et al. (this volume) on the sediment composition and distribution in the Barasona Reservoir, represent the first attempt to quantify the impacts that the reservoir exerts on the sediment transport and the C and N fluxes. However, this study has not aimed to establish a C or N yield or budget as some more work is required (through monitoring or modelling) to improve the understanding of some important biogeochemical processes (e.g. atmospheric loss, mineralisation, in-reservoir new formation of organic matter, changes on C and N because of drying/wetting cycles of the accumulated sediment) that affects nutrients' dynamics as well. For this reason, this study emphasises the need to further investigate the fluxes flowing through reservoirs, especially those like Barasona draining river catchments that supply huge amounts of suspended sediments (and associated products) and where the size, type and spatial extent of sediment sources are likely to enhance the proportion of sediment stored in the channel, thus impacting on the frequency and magnitude of sediment yields.

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Annex 2

Sedimentos e invertebrados

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RESUMEN

Los ríos mediterráneos, debido a su estacionalidad y variabilidad de precipitaciones, están altamente afectados por la regulación hidrológica. Los embalses modifican el régimen de caudal y la dinámica morfosedimentaria del cauce. Estas alteraciones suelen provocar cambios en la composición y abundancia de los macroinvertebrados bentónicos, que son indicativos de la degradación del medio, y muchas veces no pueden ser detectados mediante la utilización de índices bióticos. Por esta razón, proponemos un protocolo de muestreo y cálculo de indicadores para evaluar el impacto hidromorfológico en ríos regulados y su efecto en la comunidad de macroinvertebrados. Como ejemplo, se presenta un estudio realizado en el río Siurana para evaluar el impacto de la regulación en la hidrología, la geomorfología y la comunidad de macroinvertebrados, siguiendo una aproximación de contraste entre tramo control y tramo impactado.

SUMMARY

Mediterranean rivers, due to their seasonality and precipitation variability, are largely affected by hydrological regulation. Dams modify the fluvial regime and the channel morphosedimentary dynamics. Such alterations use to cause changes in both the composition and abundance of the benthic macroinvertebrates, which are indicatives of the degradation of the fluvial system and cannot be always detected by biotic indices. For this reason, we propose a protocol for field sampling and indices calculation in order to evaluate the hydromorphological impact in regulated rivers and its effect on the macroinvertebrates communities. As an example, we present the study case of the Siurana River to evaluate the impact of regulation in the hydrology, geomorphology and macroinvertebrate community, following an approach by comparing a control and an impacted site.

INTRODUCCIÓN

El régimen hidrológico de los ríos y otros aspectos relacionados con el hábitat como el sustrato, la calidad del agua y la temperatura son la base para mantener la biodiversidad y el equilibrio ecológico de todo el ecosistema (Booker et ál., 2015). Cuando hablamos de hábitat nos referimos a las condiciones físicas y biológicas necesarias para que las especies puedan mantener sus poblaciones en un área determinada (Begon et ál., 2005). Cada especie presenta unas características propias que hacen que su vida sea posible en un ambiente en particular y muy difícil o imposible en otros. Esto se debe a que el medio ha ido ejerciendo una fuerza de selección natural que ha moldeado y especializado la evolución de los organismos, favoreciendo la adaptación de las comunidades a las condiciones locales. Por ejemplo, los macroinvertebrados que viven en ríos mediterráneos presentan adaptaciones que les permiten sobrevivir en ambientes extremos con frecuentes crecidas torrenciales y caudales muy bajos o prácticamente secos durante alguna época del año (Bonada et ál., 2007). Algunas de estas adaptaciones son, por ejemplo: ciclo de vida corto, puesta de huevos terrestre, reproducción asexual, formas de resistencia a la sequía, respiración aérea y dispersión aérea activa (Bonada et ál., 2007; Bonada and Resh, 2013; Lobera et ál., 2016b).

La interacción entre la fuerza ejercida por el agua y las partículas del lecho es la principal característica para la generación y la conservación de los hábitats en los sistemas loticos, y por lo tanto, su análisis tiene una gran importancia desde el punto de vista del conocimiento y la conservación de los ecosistemas acuáticos. Del mismo modo, se puede determinar que los factores que más influyen en la distribución y abundancia de las especies en los ecosistemas fluviales son:

i) Las características estructurales del medio (p. ej. tamaño y distribución de las partículas, morfología del cauce). En general, ambientes con una estructura simple tienden a presentar menos riqueza de especies que ambientes con una mayor complejidad y heterogeneidad de hábitats (Taniguchi y Tokeshi, 2004).
ii) La frecuencia e intensidad de las perturbaciones. Una perturbación ocurre cuando una fuerza es aplicada sobre el espacio que ocupa una población, el hábitat puede degradarse o desaparecer y los organismos deben desplazarse o quedan gravemente afectados (Lake, 2000).

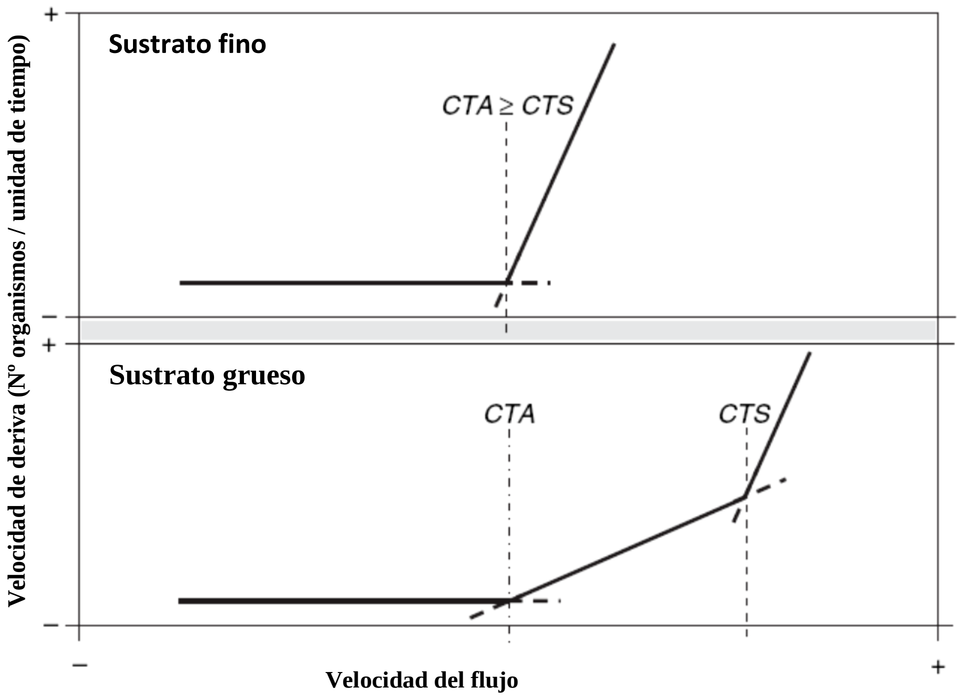
Las principales alteraciones naturales en los sistemas fluviales son las sequías y las inundaciones. Un ambiente que presente una frecuencia elevada de perturbaciones tiende a presentar menos riqueza de especies que un ambiente menos alterado. Esta relación entre la hidrología y el medio físico puede afectar de manera diferente al ecosistema dependiendo de la escala espacial a la que estemos trabajando. A escala de cuenca podemos dividir el perfil longitudinal de un río en tres zonas diferentes (Tabla 1, Petts, 2000): i) zona de erosión (cabecera, arroyos de montaña con pendiente elevada), la fuerza del agua excava los márgenes encajonando el cauce y dando lugar a tramos rectilíneos y constreñidos bastante estables, suelen presentar un único tipo de hábitat (lótico) y la biodiversidad no suele ser muy elevada; ii) zona de transporte (ríos trenzados o anastomosados), el sedimento se va depositando y transportando aguas abajo formando ríos inestables con múltiples canales, presenta dos tipos de hábitats (lótico y semilóticos), y la biodiversidad suele ser baja; iii) zona de deposición (los grandes ríos de llanuras aluviales), cauce con poca pendiente y formado principalmente por sustrato fino dando lugar a tramos meandriformes, presentan una elevada heterogeneidad de hábitats y una alta biodiversidad.

Table 1.
Características físicas y biológicas del perfil longitudinal de un río (adaptado de Petts, 2000)

	TRAMO DE CABECERA	TRAMO TRENZADO	TRAMO MEANDIFORME
Patrón del canal	Canal recto	Canales múltiples	Canal meandriforme
Estabilidad del cauce	Canal constreñido, estable	Cauce muy inestable	Canal móvil, inestable
Vegetación de ribera	Corredor ribereño estrecho	Comunidad pionera	Comunidad pionera hacia estados maduros
Hábitat acuático	Lótico	Lótico/semi-lótico	Lótico/semi-lótico/léntico
Biodiversidad	Baja-Moderada	Baja	Alta

Por otro lado, cuando se trabaja a escala de tramo (10^2 a 10^3 metros de longitud de cauce), la morfología, heterogeneidad de hábitats y las perturbaciones hidrológicas (en este caso crecidas) son los factores que determinarán la biodiversidad y la abundancia de las comunidades fluviales. De este modo, debemos analizar la estructura de un cauce como un sistema cambiante que se mantiene en un cierto estado de equilibrio, y este dinamismo es el responsable en parte de la estructura y el funcionamiento del ecosistema fluvial. De hecho, varios estudios demuestran que un cierto grado de perturbación es necesaria y mejora la calidad ecológica del tramo fluvial (Lake, 2000). Cuando se produce un aumento de caudal con suficiente capacidad para movilizar los sedimentos, estos se desplazan y se redistribuyen a lo largo del cauce generando zonas de erosión y de sedimentación. Estos procesos fluviales tienen importancia tanto a nivel de microhábitat (p. ej. rugosidad y porosidad de las partículas) como de mesohábitat (p. ej. unidades morfológicas como los rápidos y pozas). La movilidad del sustrato depende principalmente de la magnitud y la frecuencia de las crecidas y del tamaño del sedimento. Si la crecida es de baja magnitud se producirá un transporte parcial del sedimento del lecho (solo se movilizarán las partículas de menor tamaño). La mayoría de los macroinvertebrados buscaran refugio en la zona hiporreica (o subsuperficial) o en las zonas más estables del cauce (p. ej. sedimento de mayor tamaño) y recolonizarán de nuevo el tramo después de la perturbación. Los tramos con una estructura más heterogénea ofrecerán más posibilidades de refugiarse durante la perturbación que tramos más homogéneos y formados por sedimento fino (arenas y gravas). Por otro lado, si la crecida es de alta intensidad (también conocida como *catastrófica*) se producirá una movilización de todas las partículas del lecho y toda la estructura del canal quedará alterada. En este caso, el sustrato no servirá de refugio y la mayoría de los organismos acuáticos serán desplazados aguas abajo. Las perturbaciones *catastróficas* son beneficiosas para la mayoría de los ecosistemas a largo plazo ya que provocan un reajuste de todos los elementos y conservan un mosaico de diversidad con diferentes estadios de sucesión (Picket y White, 1985; Michener y Haeuber, 1998). El grado de impacto sobre el lecho y los organismos dependerá en gran medida del tamaño de las partículas del canal. Los sustratos de mayor tamaño (cantos-rocas) son más estables, ofrecen un hábitat más diverso para la colonización y son una fuente importante de alimento (el *biofilm* es más productivo en sustratos estables y la acumulación de detritus orgánicos también es mayor). Por esta razón, los ríos formados por sustrato grueso presentan una mayor riqueza y abundancia de especies que los ríos de sustrato fino (muy inestable). La Figura 1 nos muestra un modelo conceptual de deriva de macroinvertebrados durante una crecida en dos tramos con distinto tamaño de sustrato. Si el material del lecho es fino, el inicio de movimiento de las partículas coincidirá con la deriva de macroinvertebrados (Gibbins et ál., 2007). En cambio, si el material del lecho es grueso, la deriva de los macroinvertebrados presentará dos puntos de inflexión (Statzner, 1984; Robinson 2012). El primero antes de que el sustrato se empiece a movilizar debido a la fuerza que ejerce el agua sobre los organismos. El segundo coincide con la movilización del sustrato, en este caso la pérdida de macroinvertebrados del lecho aumenta de manera notable.

A parte de las características estructurales del tramo, las perturbaciones tienen menor o mayor impacto en la biota en función de las características de las especies que forman la comunidad. Ríos con régimen variable e inundaciones frecuentes presentan una comunidad bentónica mejor adaptada a estas perturbaciones que comunidades de ríos más estables (Matthaei et ál., 1996). Estas especies se caracterizan por una alta movilidad para buscar refugio durante la crecida (mayor resistencia a la perturbación) y una alta tasa de recolonización (mayor resiliencia) que les permite recuperar sus poblaciones rápidamente. Todo ello hace que un río sea un sistema considerablemente complejo y, al mismo tiempo, muy vulnerable a las perturbaciones antrópicas. Cualquiera actividad que influya en alguno de los componentes del ecosistema fluvial como la hidrología, la estructura del cauce y la continuidad sedimentaria, provocará una grave alteración en la biota favoreciendo la extensión de las especies más tolerantes y la desaparición de las especies sensibles. Actualmente, muy pocos ríos son prístinos y la mayoría acumulan una larga historia de alteraciones (Allan y Castillo, 2007).



LCM: *límite crítico de los macroinvertebrados*
LCS: *límite crítico del sedimento*

Figura 1. *Modelo conceptual de la deriva de los macroinvertebrados en tramos con diferentes tipos de tamaño de sustrato (figura adaptada de Gibbins et al., 2007).*

ALTERACIONES EN LOS ECOSISTEMAS FLUVIALES

A pesar de que el impacto de la actividad humana es apreciable en todas las regiones del planeta, la biodiversidad de los ecosistemas fluviales está especialmente afectada y sufre un mayor descenso que la mayoría de los ecosistemas terrestres (Dudgeon et ál., 2006). Su degeneración puede ser originada por la acción de factores antropogénicos como son la degradación del hábitat, la sobreexplotación de recursos hídricos, la introducción de especies exóticas, la contaminación y el cambio climático. Describir y analizar el estado de las comunidades acuáticas y cuantificar los impactos antrópicos es fundamental para poder ejecutar y evaluar correctamente las medidas de gestión. Como se ha comentado anteriormente, cuando se aplica una presión al medio, la respuesta del sistema (a nivel de comunidad o funcionamiento del ecosistema) dependerá del tipo y la intensidad de la perturbación y de la capacidad de resistencia o resiliencia de las especies presentes.

Durante el siglo XX, la mayoría de los ríos europeos se han visto afectados por una serie de actividades humanas (construcción de presas, extracción de gravas y cambios de uso del suelo) que afectan la transferencia de agua y sedimento a lo largo de la cuenca. Los embalses son las actuaciones que producen un mayor impacto hidromorfológico ya que modifican el régimen natural del río e interrumpen la cadena de transporte de sedimento. Las principales alteraciones hidrológicas incluyen cambios en la magnitud y frecuencia de las crecidas, reducción del caudal base y cambios en el patrón estacional (Petts, 1984; Batalla et ál., 2004). Además, la mayoría del sedimento queda retenido en el embalse reduciendo su capacidad y vida útil y generando un déficit de sedimento aguas abajo. La morfología del canal se ajustará al nuevo régimen de agua y sedimento hasta encontrar un nuevo estado de equilibrio. Podemos diferenciar dos tipos de alteraciones hidrológicas:

i) El agua liberada por la presa tiene suficiente capacidad para erosionar y movilizar el sedimento del cauce, pero no hay aporte de sedimento de aguas arriba. Se producirá incisión y estrechamiento del canal y cambio en la granulometría del lecho (aumenta el tamaño de las partículas; Kondolf, 1997).
ii) La magnitud y frecuencia de las crecidas se reduce, se producirá una estabilidad del lecho, y una reducción de la anchura activa y complejidad del cauce (Lobera et ál., 2015).

En un estudio que hemos realizado en dos ríos de la cuenca del Ebro (río Ésera y río Siurana) durante dos años (2011-2013) en el marco del Proyecto SCARCE-Consolider se han descrito los dos tipos de regulación y el diferente impacto geomorfológico que produce en el cauce (Figura 2; Lobera et ál., 2016a). Para el análisis se han escogido dos tramos de estudio en cada uno de los ríos, uno aguas arriba y, el otro, aguas abajo del embalse. En el río Ésera, se ha analizado el río aguas arriba y abajo del embalse de Barasona, que reduce drásticamente el caudal medio diario, la variabilidad y la frecuencia de las crecidas, pero el caudal máximo alcanzado durante los dos años de estudio es prácticamente el mismo que en el tramo sin regular. En cambio, en el río Siurana, la presa sí que reduce la magnitud de las crecidas y también altera el régimen estacional (aguas arriba el cauce está prácticamente seco durante el verano pero aguas abajo el caudal es muy alto), pero no modifica el caudal medio diario. En el primer caso, se puede apreciar una reducción del cauce activo (de 43 a 14 metros), una reducción de la disponibilidad e heterogeneidad de hábitats y un aumento de la granulometría del cauce. En el segundo caso, se produce una reducción del cauce activo causado por la intrusión de la vegetación de ribera, homogenización del tamaño de sustrato del tramo, reducción de la disponibilidad e heterogeneidad de hábitats y estabilidad del cauce.

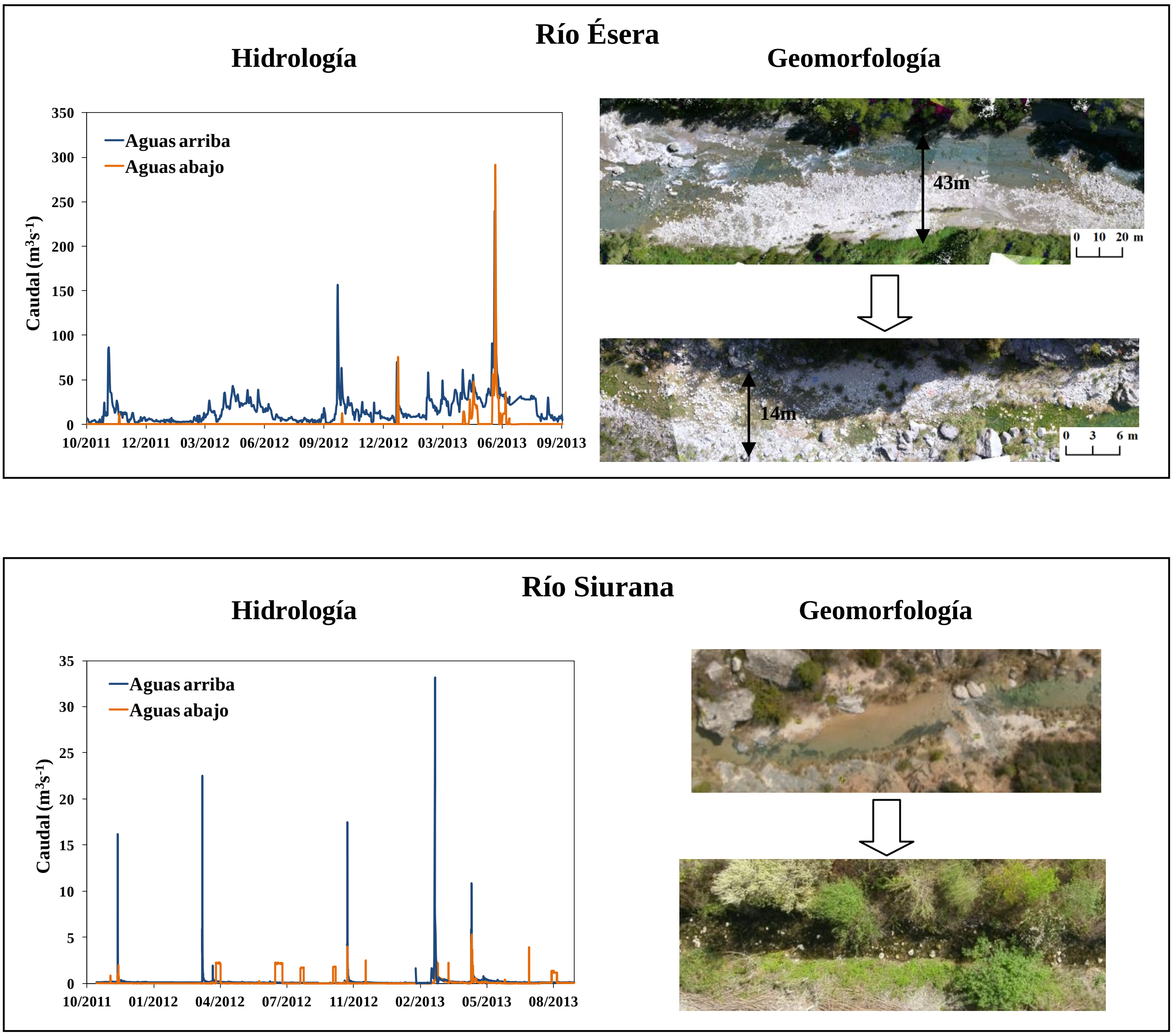


***Figura 2**. Cambios hidromorfológicos aguas abajo del enbalse de Barasona (río Ésera) y del embalse de Siurana (río Siurana).*

En ambos casos, el cambio morfológico e hidrológico del río tendrá graves consecuencias ecológicas que afectarán a todos los componentes del sistema fluvial (Kondolf, 1997). A parte del tipo de regulación, la respuesta de los ríos difiere mucho dependiendo de la ubicación, el ambiente, el sustrato y la cantidad y distribución temporal del agua (Brandt, 2000). Aunque se ha visto que el impacto de la regulación es superior en ríos de regiones áridas o semi-áridas que en ríos de zonas templadas debido a que la forma del canal y los organismos están adaptados a un ciclo anual de inundaciones y sequías.

Los ríos mediterráneos se caracterizan por presentar grandes fluctuaciones de caudal, se pueden llegar a secar en alguna época del año, y tienen frecuentes episodios de inundaciones. Estas características hacen que presenten unos ecosistemas únicos, formados por organismos adaptados a condiciones extremas, y muy sensibles a las alteraciones antrópicas. Pero estas regiones también presentan un problema de disponibilidad de agua debido a las fluctuaciones de las precipitaciones, hecho que ha provocado una construcción masiva de presas. Por ejemplo, España es el país que tiene más embalses de toda Europa (Batalla, 2003). La reducción en la magnitud de las crecidas y la modificación del régimen del caudal es la alteración más común en los ríos regulados de las cuencas mediterráneas de la península Ibérica (Batalla et ál., 2004; Lobera et ál., 2015). Este tipo de regulación hace que el río pierda todas sus características de *mediterreanidad* (ciclo anual de crecidas y sequías) degradando todo el ecosistema fluvial (ver "Caso práctico: el río Siurana").

INDICADORES PARA EVALUAR EL EFECTO DE LA REGULACIÓN FLUVIAL

Como hemos comentado en el apartado anterior, la degradación del hábitat es la alteración que provoca un mayor impacto en los ecosistemas fluviales. Los embalses alteran el régimen de caudal y la dinámica morfosedimentaria del cauce creando un hábitat uniforme y más estable desde el punto de vista hidrológico, aguas abajo. Estas alteraciones suelen provocar cambios en la composición y abundancia de los macroinvertebrados bentónicos (Ward y Stanford, 1979, 1987; Muñoz y Prat, 1989) Poff et ál., 1990). En general, la biodiversidad del tramo disminuye, se producen cambios en la estructura y funcionalidad de la comunidad (las especies lóticas son desplazadas por especies lénticas) y la densidad y biomasa de macroinvertebrados aumenta. Estos cambios son indicativos de la degradación del medio y muchas veces no pueden ser detectados mediante la utilización de índices bióticos. Por esta razón, proponemos un protocolo de muestreo y cálculo de indicadores para evaluar el impacto hidromorfológico en ríos regulados y su efecto en la comunidad de macroinvertebrados bentónicos. El análisis se lleva a cabo en un tramo al que denominamos *control* (aguas arriba del embalse) y un tramo *impactado* (aguas abajo). Consideraremos las condiciones del tramo *control* un valor relativo de referencia para la perturbación que estamos estudiando, asumiendo que este representa la situación que debería presentar el ecosistema fluvial sin la presencia de la presa. Comparando las características hidromorfológicas y biológicas del tramo impactado con los valores del tramo control, podremos determinar el impacto de la regulación.

PROTOCOLO DE MUESTREO

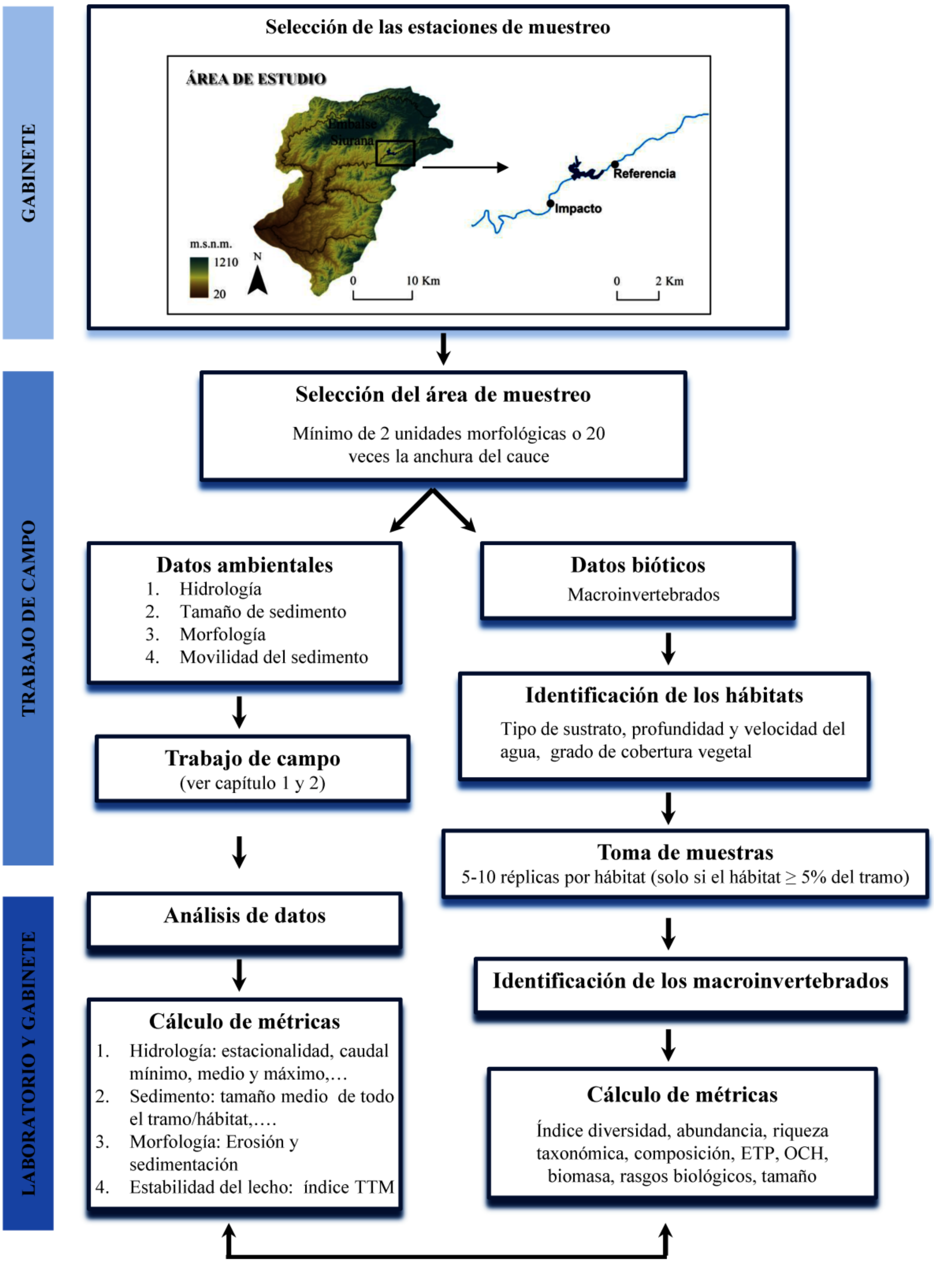


Figura 3*. Esquema general del protocolo de muestreo*

El impacto tratado en este capítulo va a ser un embalse, aunque también se podría aplicar, mediante pequeñas modificaciones, a cualquier otro tipo de perturbación antrópica. La Figura 3 presenta el esquema general que se ha seguido para el muestreo de las diferentes variables y procesos.

Indicadores hidromorfológicos

Previamente al muestreo es importante hacer una búsqueda bibliográfica exhaustiva de las características de la cuenca de estudio (precipitación, usos del suelo, fotografías aéreas). De este modo, antes de la primera visita de campo ya podremos tener localizados los posibles tramos de muestreo para el análisis biológico e hidromorfológico. Asimismo, si disponemos de fotografías históricas, podremos analizar cómo ha cambiado la morfología del cauce desde la construcción de la presa hasta la actualidad (Lobera et ál., 2015). Por ejemplo, en la Figura 4 se puede observar una serie de fotografías de un tramo del río Siurana localizado aguas abajo del embalse de Siurana (construido en 1972), donde se aprecia una reducción del cauce activo, desaparición de las barras e intrusión de la vegetación de ribera.

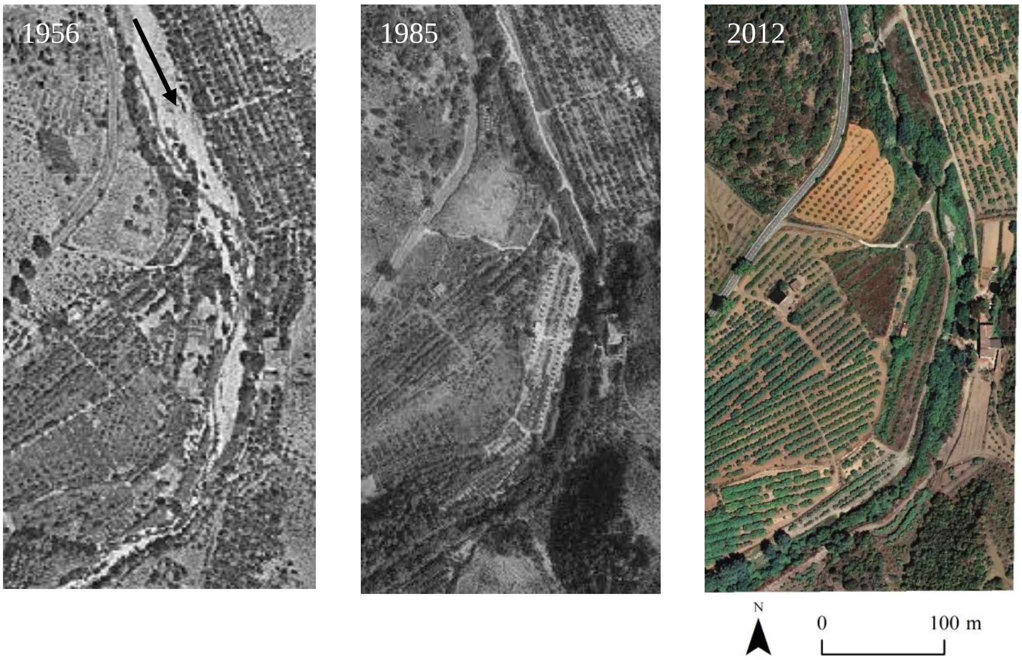


***Figura 4**. Fotografías aéreas históricas de un tramo fluvial localizado aguas abajo del embalse de Siurana. De izquierda a derecha: imagen de 1956, 1985 y 2012 (fuente: Instituto Geográfico Nacional - IGN).*

A partir de las fotografías aéreas históricas se puede calcular el estado geomorfológico del tramo de estudio mediante el *Geomorphic Status Index* (Lobera et ál., 2015). Este índice nos proporcionará un valor de degradación y estabilización del tramo y sabremos si el cauce permanece activo. También es importante tener información relativa al embalse (p. ej. año de construcción, capacidad) y analizar las series históricas de caudal aguas arriba y aguas abajo de este. De esta manera, como se ha explicado en las anteriores secciones, podremos determinar a priori el tipo de regulación así como la afectación que esta ha podido causar sobre el ecosistema fluvial en nuestro tramo de estudio. Por ejemplo, si se mantiene el patrón estacional del régimen hídrico o la magnitud y frecuencia de las crecidas.

Por lo que se refiere al trabajo de campo, el diseño metodológico lo hemos dividido en 3 bloques (información más detallada de cada uno de los métodos se puede encontrar en los capítulos 2 y 3 de este mismo libro):

i) *Caracterización granulométrica:* La composición de las partículas más gruesas del lecho (>8 mm) se caracteriza mediante el método de los transectos lineales (Wolman, 1954; Rice y Church, 1996). Este método permite la clasificación del eje b (anchura) de un mínimo de 100 partículas utilizando una plantilla que está graduada en intervalos de tamaño 1/2 phi (p. ej. Lisle y Madej, 1992). El resultado es una curva granulométrica en la que se expresa el tamaño del eje b de la partícula y su frecuencia acumulada, lo que permite extraer percentiles característicos granulométricos como la mediana (D50), o ciertos percentiles extremos de la curva (D16 o D84, siendo Di el tamaño del sedimento para el cual el i por ciento de la distribución es más fino). Por otro lado, los componentes granulométricos más finos (<8 mm) se determinan a partir de un método volumétrico. Este consiste en la extracción de un volumen determinado de sedimentos que bien son tamizados directamente en el campo o posteriormente en el laboratorio (tamices también siguiendo una distribución de luz de tamaño 1/2 phi). Los valores se clasifican en diferentes intervalos de tamaño según la escala de Wentworth, elaborando posteriormente curvas granulométricas correspondientes (igual que para el método de transectos lineales).

ii) *Caracterización morfológica:* La identificación de las unidades morfológicas se puede realizar mediante la clasificación propuesta por Montgomery y Buffington (1997) para ríos de montaña, o mediante el muestreo de hábitats de ríos propuesto por Raven et ál. (1997). Adicionalmente, se puede determinar y cuantificar la extensión de cada una de las unidades morfológicas del tramo de estudio mediante fotografías aéreas de proximidad que se pueden hacer siguiendo diferentes métodos (p. ej. autogiros, drones o globos de helio) que son posteriormente georreferenciadas y con las cuales se forma un mosaico del tramo (Vericat et ál., 2009) que servirá de mapa donde se podrán identificar y medir los diferentes hábitats mediante diferentes paquetes informáticos como, por ejemplo, ESRI® *software* ArcMap™.

iii) *Perturbación del lecho y estabilidad:* Se determina mediante el estudio de la movilidad del lecho y la evaluación de los cambios topográficos en el tramo de estudio producidos por los diferentes eventos competentes acaecidos durante un cierto período de tiempo (mínimo 1-2 años). El estudio de la movilidad se ejecuta, normalmente, mediante trazadores de distinta tipología (p. ej. trazadores pintados o sensores pasivos como los RFID). El objetivo es determinar la distancia y la trayectoria de desplazamiento de los sedimentos trazados después de cada episodio de movilidad (e. g. Church y Hassan, 1992; Vericat et ál., 2008b; Libeault et ál., 2012). Este método consiste en conocer la posición inicial y final de los trazadores (por ejemplo mediante la utilización de un GPS de doble frecuencia) para así poder calcular el vector y trayectoria de desplazamiento entre el período de tiempo en el que el trazador se instala en el campo y el periodo de reconstrucción. Es necesario también medir el tamaño de las partículas trazadas y asegurarnos de que el material trazado sea representativo de todos los componentes granulométricos móviles del cauce tras comparar este material trazado con la distribución granulométrica superficial del tramo. Los datos de los trazadores se pueden utilizar, por ejemplo, para estimar el grado de estabilidad del lecho mediante el método propuesto por Schwendel et ál. (2011). Por otro lado, los cambios topográficos del lecho se evalúan a partir de levantamientos topográficos de alta densidad y detalle del tramo de estudio realizados después de cada evento competente. Posteriormente, se crean Modelos Digitales del Terreno (MDT) de alta resolución que pueden ser comparados (MDT de Diferencia) permitiendo así determinar la magnitud, dirección y distribución del cambio asociados al evento (o eventos) sucedidos entre los levantamientos. Con estos datos se puede calcular, por ejemplo, el volumen y el área que ha sufrido erosión y sedimentación así como el cambio neto (sedimentación menos erosión) del tramo.

Indicadores biológicos

Las comunidades de macroinvertebrados presentan una gran variabilidad temporal y espacial, y esto se debe tener presente al diseñar el trabajo de campo. El muestreo biológico se debe realizar entre la primavera y principios de verano, períodos en los cuales se espera encontrar una mayor abundancia de organismos bentónicos. El protocolo de muestreo que se describe es una adaptación del método AQEM (2002), basado en un muestreo multihábitat cuantitativo.

El tramo de estudio escogido deberá presentar un mínimo de dos unidades morfológicas (p. ej. rápido-poza) o tendrá una longitud igual o mayor a 20 veces la anchura del cauce. Este debe contener elementos físicos y estructurales duplicados (p. ej. secuencia de rápido-poza) procurando que contenga el máximo número de hábitats. Los hábitats se definen en función de la combinación de las siguientes características: i) velocidad del agua; ii) tipo y tamaño de sustrato del lecho fluvial; iii) presencia y tipo de materia orgánica (*biofilm*, acumulación de hojarasca, madera, presencia de macrófitos). El muestreo de macroinvertebrados se realizará en función de la cobertura de cada hábitat. Una forma sencilla de calcularlo es mediante un marco cuadrado de, por ejemplo, un metro cuadrado. Este marco servirá para hacer varias secciones equidistantes a lo largo del tramo y calcular la velocidad, profundidad, el sustrato y la materia orgánica presente en cada una de ellas. De esta manera, se podrá calcular de una forma bastante aproximada la cobertura de cada uno de los hábitats.

La toma de muestras se realizará mediante una red Surber. El muestreo debe empezar al final del tramo e ir remontando el río para evitar alterar los organismos de las zonas que aún no hemos muestreado. Se recogerán un total de 5-10 réplicas por hábitat en función de su representatividad en el tramo (los hábitats que representen solo un 5% del tramo no se tendrán en cuenta). La muestra se lavará en el campo eliminando las piedras y otras partículas, y el resto se introducirá en potes de plástico y se conservará en formaldehído al 4% o en alcohol al 70%.

Una vez en el laboratorio, se separarán e identificarán todos los organismos hasta género o especie utilizando una lupa binocular. Si la densidad de la muestra es muy alta se pueden hacer submuestras a partir de 500 especímenes encontrados (Rodrigues et ál., 2009). Todos los individuos encontrados de cada una de las especies se enumerarán y conservarán en alcohol para su posterior análisis. Si se quiere calcular la biomasa, una de las metodologías más utilizadas es mediante las ecuaciones propuestas por Meyer (1989) y Burgherr y Meyer (1997). Estas ecuaciones relacionan el tamaño del organismo con su peso seco. Por lo tanto, si queremos utilizarlas deberemos medir los individuos.

Cálculo de métricas

A partir de la composición taxonómica y abundancias se pueden calcular diversas métricas como:

— Índices de biodiversidad (Índice de Shannon-Wiener, Índice de Simpson, Índice de Margalef)

— Riqueza de taxones (especie, género o familia)

— Abundancia y densidad de taxones (total, ETP, OCH...)

— Biomasa y tamaño de taxones

— Abundancia de algunos rasgos biológicos asociados a las especies

Todas estas métricas nos proporcionan información sobre la estructura de la comunidad pero también es posible caracterizar su funcionalidad en el sistema mediante el cálculo de los rasgos biológicos como el tipo de alimentación, ciclo de vida, reproducción o tamaño. Estas características están estrechamente relacionadas con el hábitat donde se encuentra la especie, ya que este ha actuado de filtro seleccionando aquellos rasgos que permitan la colonización y supervivencia en él (Stazner et ál., 2004). El análisis de los rasgos biológicos permite comparar estudios a gran escala (distintas ecoregiones) porque no están influenciados por la localización geográfica, a diferencia de la composición taxonómica. Todos los rasgos biológicos se obtienen de información bibliográfica. Actualmente existen algunas bases de datos con información biológica detallada de todas las especies de diferentes regiones del mundo (p. ej. en Europa: Tachet et ál., 2002). Para profundizar en el cálculo y el análisis de los rasgos biológicos se recomienda consultar Usseglio-Polatera et ál., (2000), Rodrigues-Capitulo et ál. (2009), Statzner y Bêche (2010).

CASO PRÁCTICO: EL RÍO SIURANA

En el contexto explicado a lo largo de este capítulo, se ha realizado un estudio para evaluar el impacto de la regulación en el río Siurana durante el ciclo hidrológico 2011-2013. El principal objetivo fue el estudio de las relaciones existentes entre el régimen de caudal, los cambios geomorfológicos y la respuesta de la comunidad de macroinvertebrados, siguiendo una aproximación de contraste entre tramo control y tramo impactado. Se analizaron los cambios en el patrón de caudal causado por la presa de Siurana, se examinó la influencia que ejerce la regulación sobre el lecho y su estabilidad y, finalmente, se detalló la composición y densidad de la comunidad de macroinvertebrados y sus rasgos biológicos, en dos tramos del río situados aguas arriba de la presa (tramo control) y aguas abajo (tramo impactado).

El río Siurana es el principal tributario del tramo bajo del Ebro (NE de la Península Ibérica). La cuenca presenta una superficie de 610 km^2 con una precipitación media anual de 500 mm. El clima es muy mediterráneo, caracterizado por un período muy seco durante el verano y precipitaciones torrenciales durante la primavera y el otoño. El embalse está situado en la parte superior de la cuenca, recogiendo el agua del 12% del área. La presa se completó en 1972 con una capacidad máxima de almacenamiento de 12 hm^3. El trabajo de campo se ha llevado a cabo en dos tramos del río Siurana, el tramo control localizado 1 km aguas arriba del embalse de Siurana y el tramo impactado a 2 km debajo de la presa (Figura 5).

Figura 5*. Vistas generales de los tramos de estudio en las que se pueden observar diferencias en la cobertura y tipo de vegetación, y la estructura morfológica del cauce.*

En el tramo no regulado, el río presenta un caudal medio de 0,14 m^3s^{-1}, con un mínimo de 0,02 m^3s^{-1} y un máximo de 30 m^3s^{-1} durante el periodo de estudio. Si lo comparamos con los valores de caudal del tramo regulado, observamos que el caudal medio anual es muy similar (0,12 m^3s^{-1}). En cambio, el valor máximo para el mismo periodo es de 5,8 m^3s^{-1}, lo que corresponde a una reducción del 82% respecto al valor del tramo control. El patrón estacional también ha sido alterado, sobre todo en verano cuando el río está prácticamente seco en el tramo control, pero en el impactado el caudal es alto debido a la abertura de las compuertas con el fin de subministrar agua para riego. Finalmente, en cuanto a la composición química del agua, Aristi et ál. (2014) observaron diferencias estadísticamente significativas pero biológicamente irrelevantes en la conductividad del agua y oxígeno disuelto entre el tramo control e impactado.

La metodología empleada en este estudio la hemos dividido en tres bloques (para más información ver Lobera et ál. 2016b):

i) Caudal y parámetros de hábitat

Se han instrumentado los dos tramos de estudio con un sensor de altura de agua (TruTrack® WT-HR) que nos ha permitido calcular el caudal mediante una recta de calibración (caudal-altura de agua). Se ha medido la distribución del tamaño de las partículas superficiales del lecho mediante el método de recuento de gravas (Wolman, 1954) para los componentes granulométricos más gruesos y el método volumétrico para los componentes finos. También se han realizado fotografías aéreas de proximidad. Estas se han georreferenciado y se ha creado un mosaico de todo el tramo según el método de Vericat et ál. (2009), lo que nos ha permitido describir y calcular la extensión de cada una de las unidades morfológicas.

ii) Perturbación del lecho y estabilidad

Se ha evaluado mediante el estudio de la movilidad de las partículas utilizando trazadores pintados y RFID (localizando su posición antes y después de cada evento) y mediante el análisis de los cambios en la morfología del río (análisis de los cambios topográficos entre los eventos competentes) utilizando un GPS diferencial Leica® GNSS/GPS y una estación total robótica Leica® TCRP1201.

iii) Macroinvertebrados

Se realizó una campaña de muestreo intensiva durante la primavera del 2012. Se recogieron un mínimo de 6 muestras por hábitat en cada uno de los tramos. Los hábitats se caracterizaron mediante el tipo de sustrato y la velocidad del agua. Para el muestreo se utilizó una red Surber y se fijaron las muestras con alcohol 70º. La biomasa se estimó mediante la conversión de tamaño-peso seco, es decir, se midió la longitud del cuerpo o cabeza de cada individuo y se relacionó con el peso seco (mg) mediante la aplicación de una recta de regresión específica para cada taxón (Meyer, 1989; Burgherr y Meyer, 1997). También se seleccionaron 7 rasgos biológicos para examinar el efecto de la regulación en las características de la comunidad de macroinvertebrados (Tachet et ál., 2002). Los rasgos seleccionados están relacionados con: historia vital (duración del ciclo de vida, dispersión), fisiología (tipo de alimentación), preferencia de hábitats (temperatura, microhábitat y flujo) y movilidad (tipo de locomoción y relación con el sustrato). Se aplicó un análisis de la varianza con un factor (ANOVA) para determinar las diferencias estadísticamente significativas entre el tramo control e impactado.

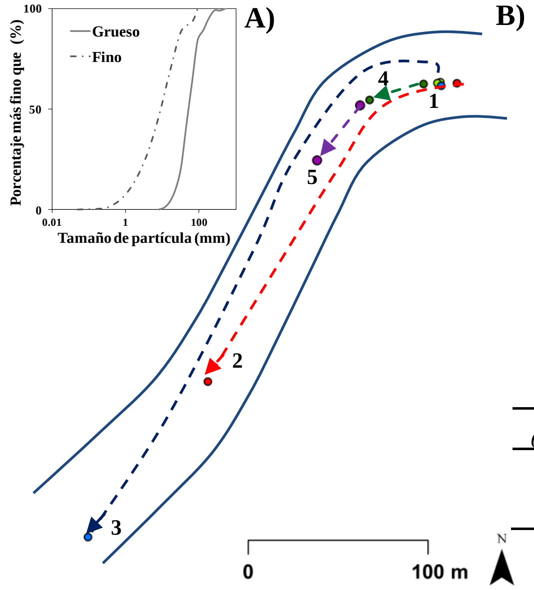
Resultados

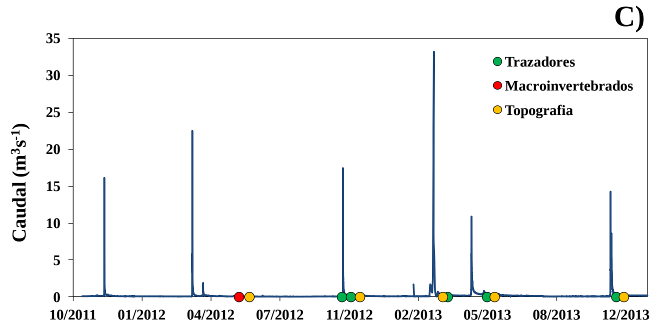
Cambios en el patrón del caudal, estructura y estabilidad del lecho

En cuanto a la distribución de hábitats, se observaron tres ambientes diferentes en el tramo control en función del tipo de sustrato y velocidad del agua: i) sedimento fino (arena y gravas finas) presente principalmente en zonas de flujo lento, profundo (pozas) y somero (tablas); ii) partículas gruesas presentes principalmente en zonas de corriente (rápidos); y iii) roca madre. En cambio, el tramo impactado es muy homogéneo presentando un solo tipo de sustrato (partículas gruesas) y sin cambios de profundidad ni de velocidad del agua. La distribución granulométrica de los dos tramos se puede observar en la Figura 6 (A, F). Según la clasificación de Montgomery y Buffington (1998), el tramo no regulado se puede clasificar como un tramo con una tipología *riffle-pool* y el tramo regulado como *plane-bed*.

En el tramo control se registraron 6 eventos durante el período de estudio, 5 de los cuales fueron monitorizados para determinar la estabilidad del cauce (movilidad de los trazadores y cambios topográficos, Figura 6C). El evento de mayor magnitud fue registrado el 6 de marzo de 2013 con un caudal máximo de 33 m^3s^{-1}, las otras inundaciones fueron de una magnitud significativamente menor (17 m^3s^{-1}, 14 m^3s^{-1}, 10 m^3s^{-1}, 0.3 m^3s^{-1}). Se recogieron un total de 133 trazadores durante todo el período de estudio. El tamaño (eje-*b*) más grande de la partícula que fue movilizada fue de 220 mm, y el desplazamiento más largo fue de 340 m. Todos los eventos excepto uno (el de 0.3 m^3s^{-1}) fueron capaces de movilizar una partícula mayor que el D50 (percentil 50) de la fracción gruesa del cauce, lo cual indica que se han movilizado la mayoría de los componentes granulométricos (móviles). Además, la distancia máxima desplazada fue entre 30 y 340 m (Figura 6B), lo que determina un grado de perturbación elevado. Por otro lado, mediante la comparación de los levantamientos topográficos realizados antes y después de cada evento, determinamos los cambios morfológicos en el canal. La Figura 6D muestra los valores de erosión y deposición y el correspondiente pico máximo de la crecida, los valores son bastante pequeños seguramente debido a los procesos de compensación que han tenido lugar durante el evento y que no se pueden determinar con esta metodología. Podemos concluir que el tramo control presenta una estructura del cauce muy inestable, el sustrato es movilizado frecuentemente y el grado de perturbación es elevado como hemos podido apreciar por la distancia que han recorrido los trazadores en cada evento.

Tramo control

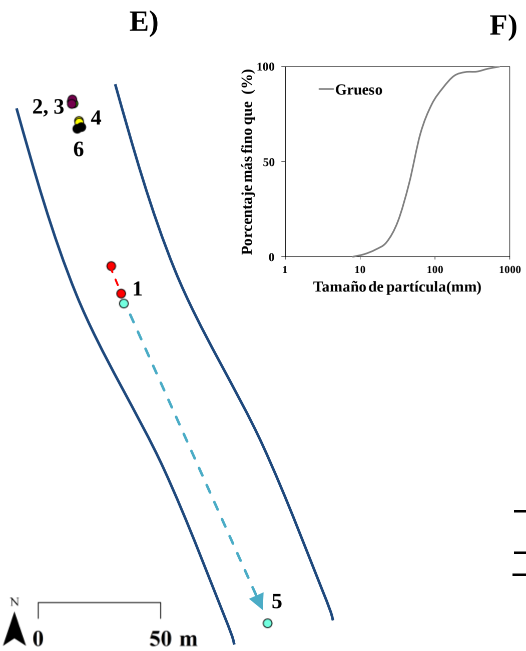


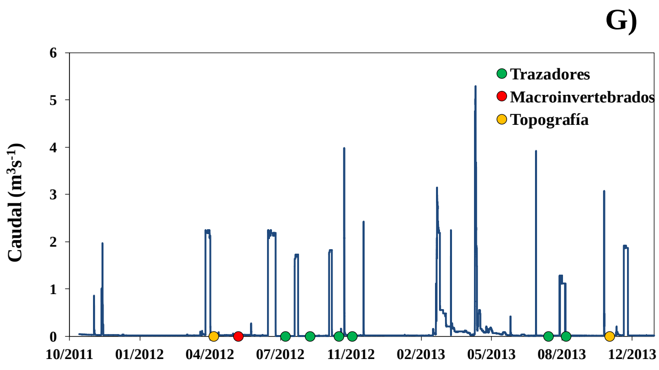


D)

Qci (m^3s^{-1})	Erosión (m^3)	Erosión media (m)	Sedimentación (m^3)	Sedimentación media (m)	Cambio neto (m^3)
17	66	0.4	76	0.3	10
33	57	0.3	30	0.3	-27
11	29	0.3	21	0.3	-8
14	41	0.5	49	0.6	8

Tramo impactado





H)

Qci (m^3s^{-1})	Erosión (m^3)	Erosión media (m)	Sedimentación (m^3)	Sedimentación media (m)	Cambio neto (m^3)
6	4	0.2	3	0.2	-0.5

Figura 6. *Características hidromorfológicas del tramo control (no regulado) y el tramo impactado (regulado) en el río Siurana. En cada uno de los tramos de estudio hemos analizado: i) la distribución del tamaño de las partículas (A,F); ii) la movilidad de los trazadores durante el período 2011-2013 (B, E); iii) el régimen de caudal donde se han señalado las fechas del muestreo de macroinvertebrados, trazadores y topografía (C, G); iv) la erosión y sedimentación del tramo después de cada muestreo topográfico (D, H).*

En el tramo impactado, se registraron 11 crecidas de similar magnitud (caudal máximo osciló entre 1.2 y 5.8 m^3s^{-1}) durante el periodo de estudio. De estas, siete fueron monitorizadas para el estudio de movilidad de las partículas. Un total de 162 trazadores fueron recolectados, siendo el tamaño de la partícula más grande movilizada de 150 mm y 143 m la distancia de desplazamiento más larga. Todos los eventos fueron capaces de movilizar partículas más grandes que el D50 del sustrato superficial pero los valores de desplazamiento fueron muy pequeños y prácticamente no hubo ningún cambio topográfico. Por lo tanto, podemos concluir que el grado de perturbación durante todo el período fue muy bajo y podemos considerar que es un tramo muy estable y geomorfológicamente inactivo (Figura 6E, H).

Cambios en la comunidad de macroinvertebrados

Se identificaron un total de 46 taxones, 33 en el tramo control y 37 en el impactado. La riqueza taxonómica, densidad y biomasa por muestra difiere significativamente entre los dos tramos (ANOVA, p<0,001; Figura 7). El tramo control presentó los valores medios más bajos (9 taxones, 734 ind m^{-2} y 145 mg m-2), en comparación con los valores observados en el tramo impactado (20 taxones, 31500 ind m-^{2} and 3850 mg m^{-2}). El índice de diversidad de Simpson es considerablemente menor en el tramo impactado (3.3) que en el de control (5).

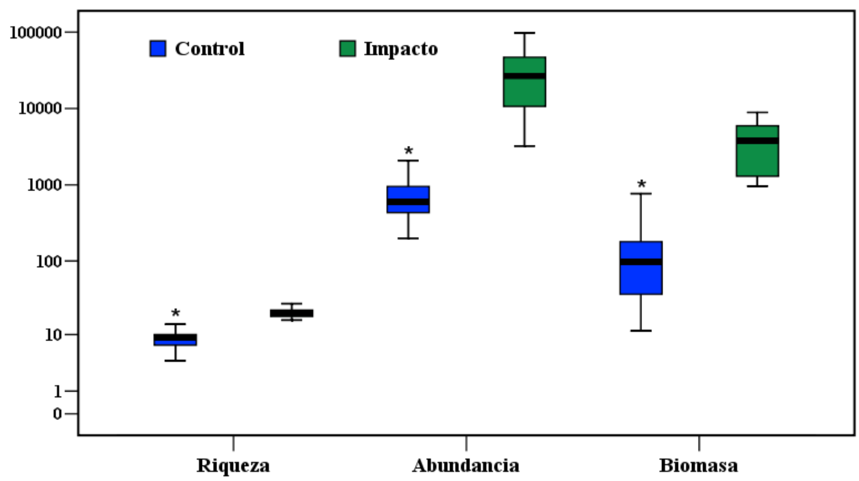


***Figura 7**. Diagrama de cajas de la riqueza (número de taxones por muestra), abundancia (número de individuos por m^2) y biomasa (peso seco por m^2) del tramo contro e impactado del río Siurana. Los asteriscos muestras las diferencias significativas (ANOVA, p<0.001).*

La familia más abundante en los dos tramos es *Chironomidae,* representa el 20% de la comunidad del tramo control y el 43% en el tramo impactado. Cuando comparamos los taxones de EPT en cada tramo, estos predominan en el control (58%), siendo los plecópteros los más abundantes, pero no en el impactado (43%), siendo el efemeróptero *Baetis* el más abundante. Si analizamos la densidad de los taxones que están presentes en los dos tramos observamos que 14 de los 16 taxones presentan un aumento significativo en el tramo impactado por un factor de tres o más. Además, el tamaño medio de los macroinvertebrados generalmente es significativamente más grande en el tramo impactado (Tabla 2).

Tabla 2.
Valores medios del tamaño y resultados del ANOVA para contrastar las diferencias entre tramos. La tabla incluye los resultados de las especies más abundantes y comunes en los dos tramos de estudio.

Taxon	**Promedio tamaño C (mm)**	**Promedio tamaño I (mm)**	**F**	**p-valor**
Baetis sp.	0.43	0.47	1.31	0.26
Caenis sp.	0.66	0.77	6.90	0.01*
Habrophlebia sp.	0.59	0.87	6.50	0.03*
Hydropsyche sp.	0.88	0.50	14.19	<0.01**
Leuctra sp.	0.41	0.70	291	<0.01**
Limnius sp.	0.2	0.19	0.04	0.83
Onychogomphus uncatus	1.71	1.09	1.25	0.28
Orthocladiinae	2.68	2.99	2.96	0.09
Polycentropus sp.	0.66	1.03	17.09	<0.01**
Simuliidae	2.36	2.64	0.40	0.53
Tanypodinae .	3.2	4.56	25.92	<0.01**

Por otro lado, nueve taxones encontrados en el tramo control no aparecen en el impactado, principalmente especies de coleópteros y efemerópteros. Pero 15 nuevas especies aparecen aguas abajo de la presa, entre las que destacan por su abundancia: *Gammarus sp.*, *Potamopyrgus antipodarum*, *Ancylus fluviatilis* y *Haplotaxidae*.

En cuanto a los resultados obtenidos con el estudio de los rasgos biológicos, no observamos diferencias entre las dos comunidades. Sin embargo, cuando se analizaron los rasgos de los taxones que solo aparecían en uno de los tramos, encontramos que la comunidad del tramo control se caracterizaba por taxones con diseminación aérea activa, lo que permite su dispersión a nuevos entornos cuando las condiciones son desfavorables (inundaciones y sequía). En cambio, en el tramo impactado predominaban los taxones con diseminación acuática.

Relación entre el régimen de caudal, la respuesta geomorfológica y las características de la comunidad de macroinvertebrados

Estudios previos demuestran que las densidades de macroinvertebrados tiende a ser más bajas en aquellos ríos donde la frecuencia de las inundaciones es alta (p. ej. Schwendel et ál., 2011; Lake, 2000; Robinson, 2012). Este es el caso del Siurana, donde las frecuentes inundaciones son capaces de movilizar todo el sedimento del cauce y, por lo tanto, la mayoría de los macroinvertebrados que residen. La presa reduce la frecuencia y magnitud de los eventos, causando una disminución de la perturbación del cauce. Esto explicaría el incremento en la biomasa y densidad de macroinvertebrados en el tramo regulado. Además, la estabilidad del sustrato junto con flujos constantes está generalmente asociada con altas cantidades de biomasa de algas en el biofilm que cubre el substrato (Poff et ál., 1990), fenómeno observado aguas abajo del Siurana por Ponsatí et ál. (2014) (Figura 8).

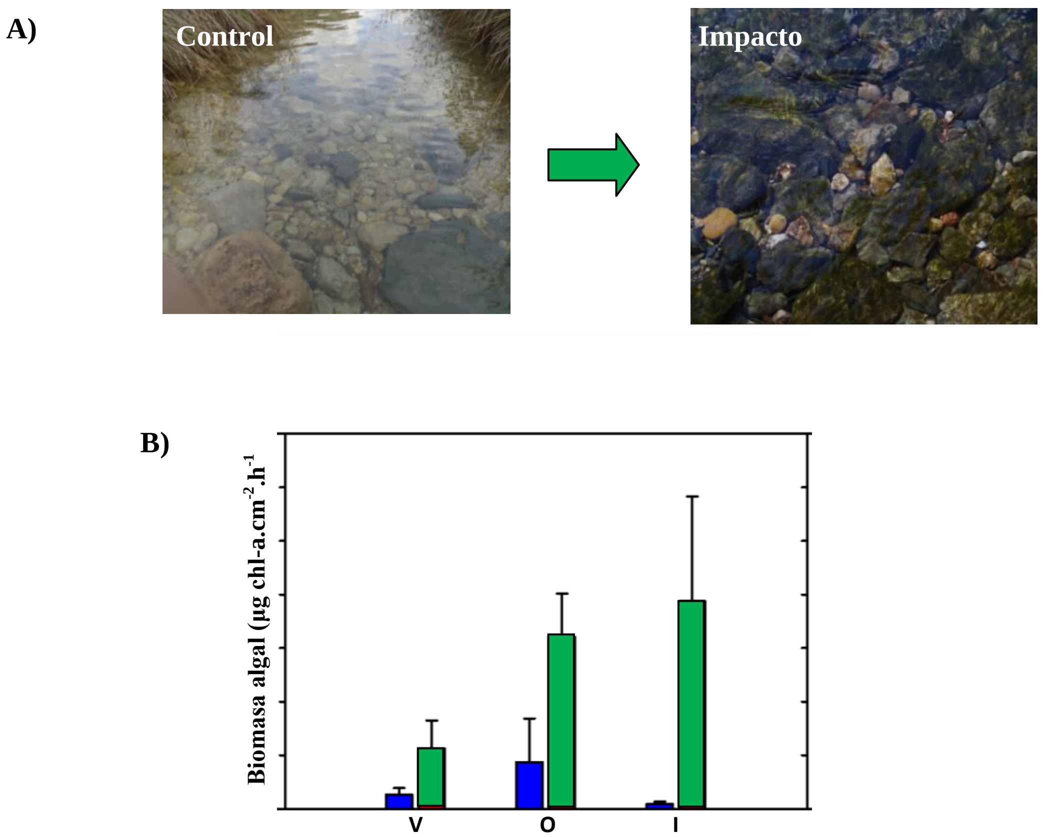


Figura 8. *A) Imagen del sustrato en el tramo control e impactado, donde se puede apreciar la diferencia en el perifiton; B) Biomasa algal estimada a partir de la concentración de Chl-a por unidad de área y tiempo de muestreo (V: verano, O: otoño, I: invierno), en el tramo control (no regulado) e impactado (regulado) del rio Siurana (Ponsatí et al., 2014).*

Las algas suministran alimento y sirven de refugio para muchos invertebrados (Moog, 1993). El aumento de la biomasa algal explicaría algunas de las diferencias en la composición taxonómica observadas entre los dos tramos. *Ephemerella*, *Baeti*s y *Gammarus* son más abundantes en el tramo impactado y aparecen gasterópodos predominantemente herbívoros. Además, la alta disponibilidad de alimento y las condiciones estables en el tramo impactado favorecen el aumento del tamaño de los individuos. Sin embargo, estas condiciones restringen otras especies como las de la familia *Heptageniidae*. En el tramo control la biodiversidad es más alta, aunque no el número de taxones, lo que indica que la abundancia está repartida más equitativamente entre los taxones en este tramo.

Agradecimientos

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Annex 3

PICTURES

1. Study sites

Figure 1. *Photographs of the two study reaches located upstream (ESE_{US}; A, B; photos: G. Lobera) and downstream (ESE_{DS}; C, D; photos: G. Lobera) of the Barasona Reservoir (Ésera River).*

Figure 2. *Photographs of the two study reaches located upstream (SIU$_{US}$; A, B; photos: G. Lobera) and downstream (SIU$_{DS}$; C, D; photos: G. Lobera) of the Siurana Reservoir (Siurana River).*

2. Fieldwork

2.1 River discharge

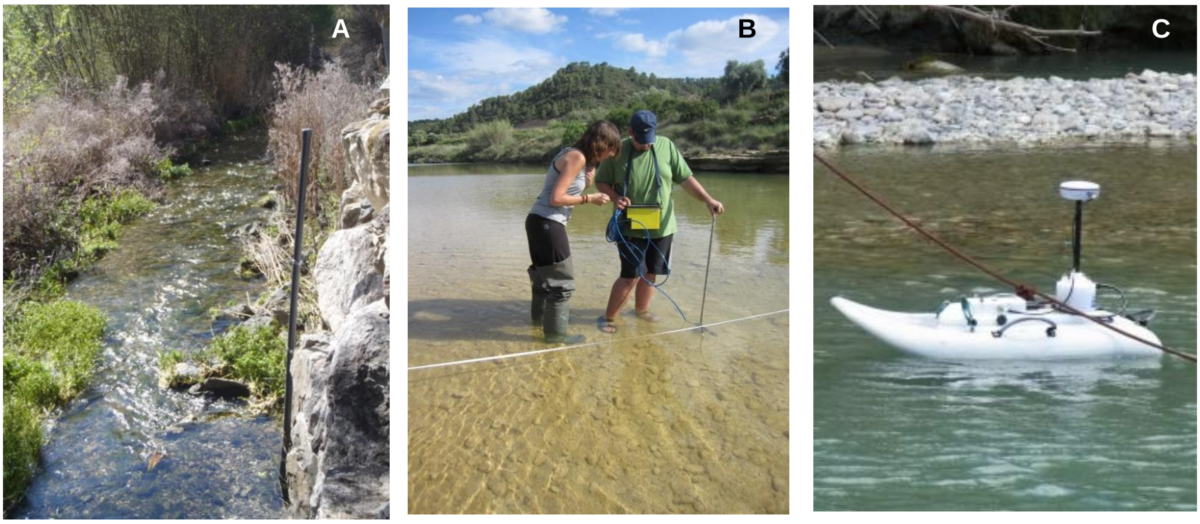

Figure 3. *(A) Water stage sampler (i.e., Trutrack®; photo: G. Lobera) installed inside the dark PVC tube; (B) Electromagnetic current meter Valeport® 801 (photo: A. Tena); (C) Acoustical Doppler current meter ADCP (e.g., River Surveyor M9; photo: G. Lobera).*

2.2 Suspended sediment concentration

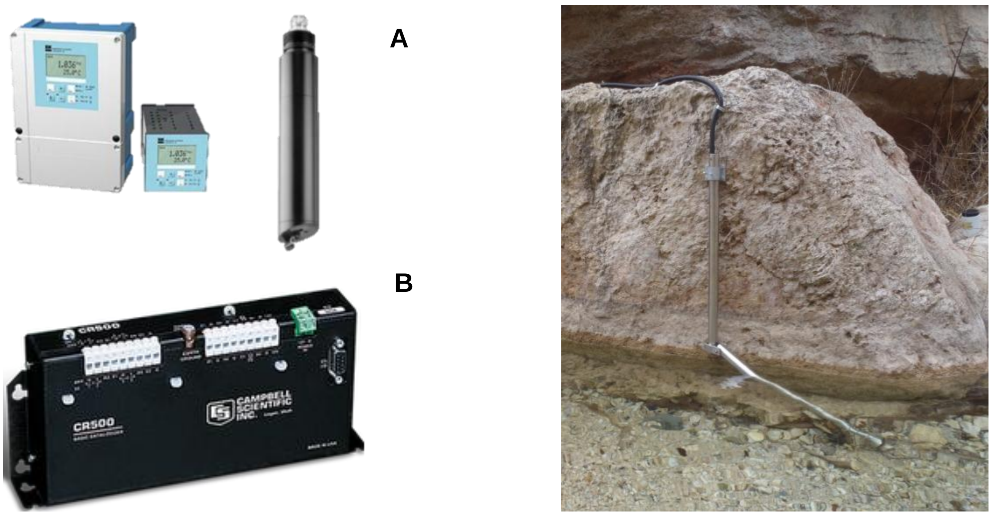

Figure 4. *(A) Endress+Hausser® Turbimax WCUS41; (B) Campbell Datalogger® CR-500; (C) Photograph of the SIU$_{US}$ suspended sediment transport installation used as an example; the turbidimeter is inside the metallic tube (photo: G. Lobera).*

2.3 Grain size distribution

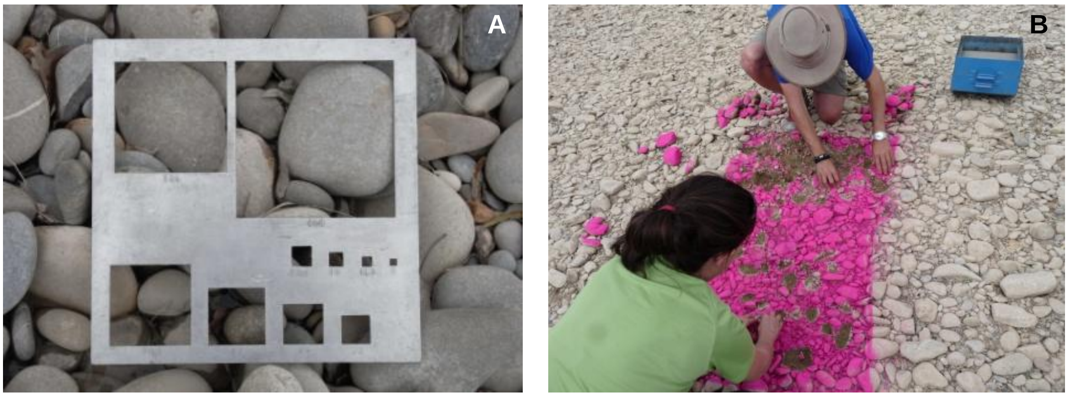

Figure 5. *(A) Wolman pebble count standard frame (photo: D. Vericat); (B) volumetric method sampling (photo: G. Lobera).*

2.4 River bed mobility

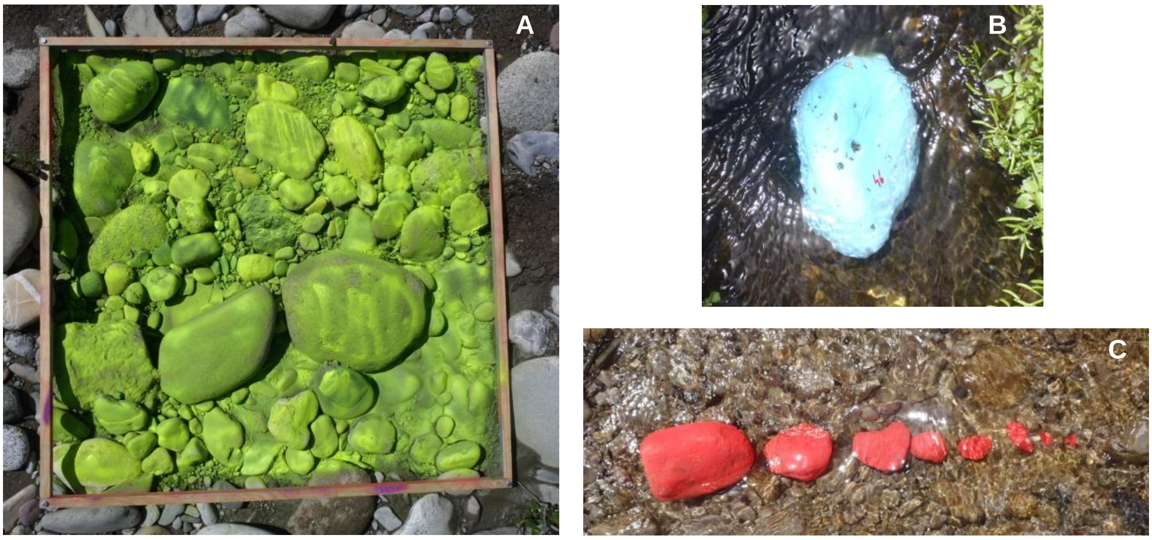

Figure 6. *(A) Painted tracers area located in* $ESE_{US;}$ *(B) tracer with a radio system in* SIU_{DS}*, and (C) line of painted tracers in* SIU_{US} *(photos: G. Lobera).*

2.5 River bed topography

Figure 7. *(A) Terrestrial Laser Scan Leica® ScanStation C10; (B) Leica® TCRP1201 Robotic Total Station; (C) Base of the Leica® GNSS/GPS; (D) Rover of the Leica® GNSS/GPS getting statically the coordinates of a reference point (photos: G. Lobera).*

2.6 Reach aerial photography

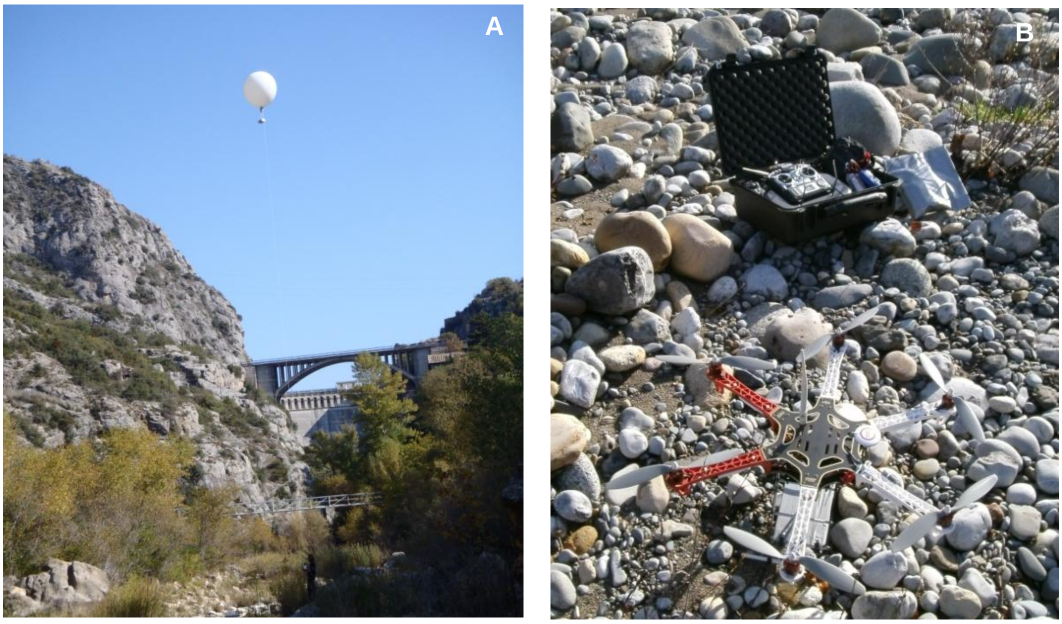

Figure 8. *(A) Digital camera attached to helium balloon; (B) hexacopter (photos: G. Lobera).*

2.7 Invertebrate sampling

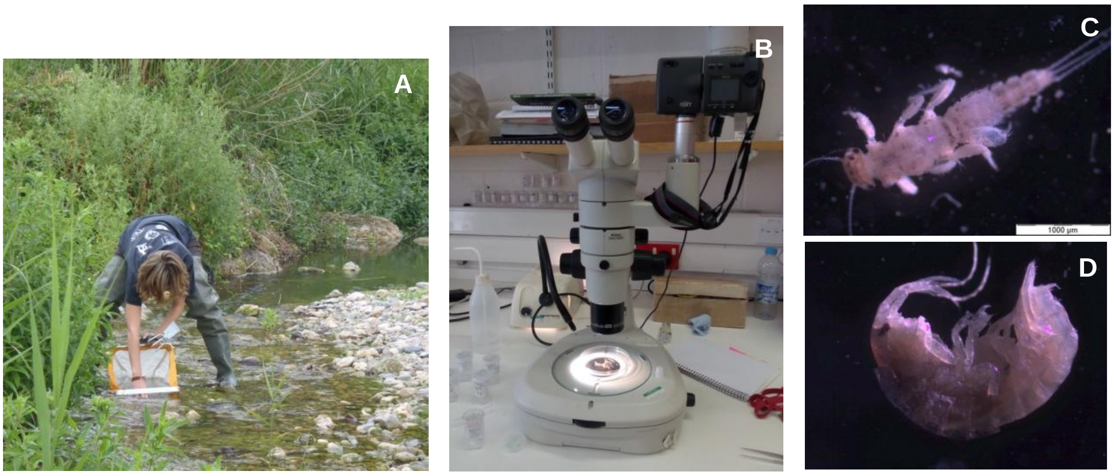

Figure 9. *(A) Invertebrate sampling using the Surber sampler (photo: JA. López); (B) Identification of invertebrate taxa (photo: M. Béjar); (C) Caenis sp. located in* SIU_{US} *and* $SIU_{DS;}$ *(D) Gammarus sp. located in* SIU_{DS} *(photos: G. Lobera).*