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Sediment transport in two mediterranean regulated rivers

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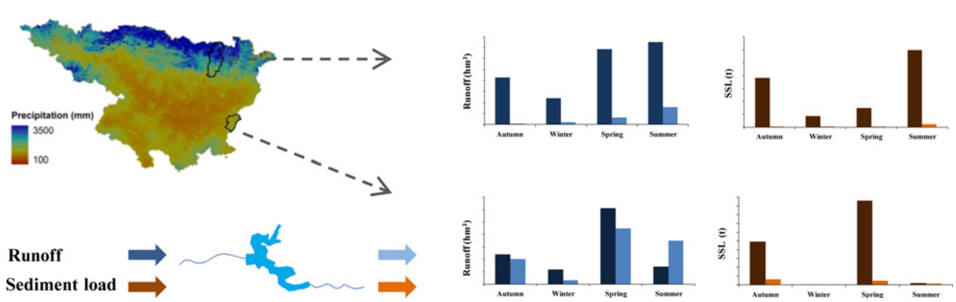
HIGHLIGHTS

- Reservoirs in the Ésera and Siurana reduce sediment load by two orders of magnitude.
- Average sedimentation in the Barasona Reservoir reaches 300,000 tons per year.
- Total runoff below the dam is only reduced in the case of the Ésera.
- The River Ésera losses its natural flow variability downstream from the dam.
- The Siurana changes its flashy regime to a constant flow below the dam.

GRAPHICAL ABSTRACT



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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 3500 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.

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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 3500 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, 1995; Petts, 1984; Ligon et al., 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.

2.1. The Ésera basin

The Ésera is a mountainous catchment located in the South Central Pyrenees. It drains an area of 1484 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 3400 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 2500 mm at the summit (the average value for the whole catchment is 1070 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