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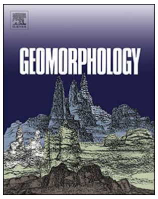

The fluvial sediment budget of a dammed river (upper Muga, southern Pyrenees)

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ABSTRACT

Many rivers in the Mediterranean region are regulated for urban and agricultural purposes. Reservoir presence and operation results in flow alteration and sediment discontinuity, altering the longitudinal structure of the fluvial system. This study presents a 3-year sediment budget of a highly dammed Mediterranean river (the Muga, southern Pyrenees), which has experienced flow regulation since the 1969 owing to a 61-hm^3 reservoir. Flow discharge and suspended sediment concentration were monitored immediately upstream and downstream from the reservoir, whereas bedload transport was estimated by means of bedload formulae and estimated from regional data. Results show how the dam modifies river flow, reducing the magnitude of floods and shortening its duration. At the same time, duration of low flows increases. The downstream flow regime follows reservoir releases that are mostly driven by the irrigation needs in the lowlands. Likewise, suspended sediment and bedload transport are shown to be notably affected by the dam. Sediment transport upstream was mainly associated with floods and was therefore concentrated in short periods of time (i.e., > 90% of the sediment load occurred in < 1% of the time). Downstream from the dam, sediments were transported more constantly (i.e., 90% of the load was carried during 50% of the time). Total sediment load upstream from the dam equalled 23,074 t, while downstream it was < 1000 t. Upstream, sediment load was equally distributed between suspension and bedload (i.e., 10,278 and 12,796 t respectively), whereas suspension dominated sediment transport downstream. More than 95% of the sediments transported from the upstream basins were trapped in the reservoir, a fact that explains the sediment deficit and the river bed armouring observed downstream. Overall, the dam disrupted the natural water and sediment fluxes, generating a highly modified environment downstream. Below the dam, the whole ecosystem shifted to stable conditions owing to the reduction of water and sediment loads.

1. Introduction

A sediment budget describes and quantifies the spatial and temporal distribution of sediment produced, eroded, stored, and transferred within a drainage basin and, ultimately, exported out of it (Dietrich and Dunne, 1978; Dietrich et al., 1982; Slaymaker, 2003). Rivers and their sediment loads are central components of basins' sediment budgets and provide useful information of the effects of human interventions in the catchment, such as reservoir siltation and the consequent sediment deficit below dams, instream gravel mining, and river training among others (e.g., Kondolf, 1997; Vericat and Batalla, 2006). Sediment budgets have also proven to be fundamental for interpreting biophysical processes in river channels, e.g., fish habitat suitability, river bed structure and clogging, and invertebrate drift and vegetative succession (e.g., Trimble, 2004; Merz et al., 2006; Buendia et al., 2014). The amount of sediment generated in a basin, and subsequently transported through the drainage network, depends on the catchment area, climate, lithology, land uses, and in general, related human activities (e.g., Kesel et al., 1992). Overall, atmospheric factors play a central role in controlling runoff generation and soil erosion and are the main cause of the intra-annual variability in sediment yields (Nadal-Romero et al., 2015). In particular, and from a worldwide perspective, erosive processes are relatively more intense in Mediterranean basins, as has been reported extensively (e.g., Inbar, 1992; Walling and Webb, 1996; Gallart et al., 2005; Lopez Saez et al., 2011; López-Tarazón et al., 2011; Vanmaercke et al., 2011; García-Ruiz et al., 2013; Vachtman et al., 2013), while

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most of the sediment is generally transported during a few events (i.e., time-compression of erosion processes is acute; e.g., González-Hidalgo et al., 2007, 2013).

Sediment budgets have mainly focused on the particulate sediments that are transported in suspension (Richards, 1982), but dissolved loads and bedloads may also represent an important proportion of the total sediment load. The dissolved load in a river is the product of inputs from rainfall and dry deposition (Meybeck, 1983), rock and soil weathering (Drever, 1982), and biogeochemical processes derived from natural processes and human activities (Farley and Werritty, 1989). Dissolved load dominates the denudation processes in forested areas of humid climates (Sala and Wheeler, 1988; Farley and Werritty, 1989). Bedload is usually a small part of the total load (around 10%, on average), but values range from below 1% in lowland rivers to up to 70% in mountain streams (Richards, 1982). Transport of fine sediments occurs in relation to erosional processes in the upstream basin and is referred to as *wash-load*, typically transported in suspension almost continuously (concentrations may be high even in some low flows; e.g., López-Tarazón et al., 2011).

Suspended sediment transport was typically measured by means of direct sampling until the 1980s, when continuous records could be obtained through optical turbidity sensors (Downing, 2006). The main advantage of continuous measurements is that they allow improved estimations of sediment loads, in comparison to the statistical procedures that must be used when only discrete samples are available. However, turbidity records require individual and in situ calibration, as several factors affect sensor readings (Downing, 2006; Minella et al., 2008; Merten et al., 2013; Regüés and Nadal-Romero, 2013). Unlike suspended sediment, bedload transport is not continuous and generally occurs only during floods. The measurement of bedload has numerous technical difficulties (Hubbell, 1987), and bedload data are sparse and discontinuous. In light of these practical shortcomings, a number of equations have been developed, most of them derived from flume experimental data (e.g., Brown, 1950; Hamamori, 1962; Wong and Parker, 2006); whereas others also considered field observations (Gomez and Church, 1989). Numerous equations focus on the bedload discharge prediction in gravel-bedded rivers in which the role of armour layers and the grain size distribution of sediment mixtures need to be carefully determined prior to model application (e.g., Bathurst, 2007). Several works have been undertaken to test the predictive power of bedload equations and its applicability to the estimation of rivers' load (e.g., White et al., 1975; Batalla, 1997; Habersack and Laronne, 2002; Barry et al., 2008; López et al., 2014, 2015).

Fluvial sediment budgets have been developed at different scales, ranging from the catchment (e.g., Loughran et al., 1992; Batalla et al., 1995; Lobera et al., 2016), to regional (e.g., Vanmaercke et al., 2011; Buendia et al., 2016), and continental/planetary (e.g., Walling, 2008) scales. In Europe, dissolved load dominates in rivers of temperate regions, while European Mediterranean rivers are controlled by suspended loads, owing to the more intense erosion processes in the basin (Milliman, 2001). There, rainfall episodes are often short but intense, triggering soil detachment and transport in sparsely vegetated areas. Further, water scarcity in this region has historically triggered the building of reservoirs for agricultural and urban purposes, so most rivers in the western Mediterranean are dammed (Beaumont, 1978). One of the main effects of dams is the reduction of flood magnitude and frequency (e.g., in California, Kondolf and Batalla, 2005; in the Mediterranean, Batalla et al., 2004; Piqué et al., 2016), and consequently, the sediment budget of the dammed river becomes altered (e.g., Williams and Wolman, 1984; Vericat and Batalla, 2006). Typically, the large part of the sediment transported through the fluvial network is retained in the reservoir and the sediment transfer is interrupted downstream, particularly the bedload, which is completely trapped. In addition, the lack of river bed disturbance in reaches downstream from dams progressively leads to stabilisation (e.g., Vericat et al., 2006; Draut et al., 2011; Lobera et al., 2016). The reduction of hydrologically active areas and substratum heterogeneity and complexity has implications for the ecosystem functioning, as energy fluxes change, potential habitat is reduced (Graf, 2006; Batalla and Vericat, 2013) and water quality is altered (Goodwin et al., 2006).

A greater understanding of the effects of global change on river basins requires further efforts to quantify flow and sediment fluxes through drainage networks. Working hypotheses are that the water and sediment budgets are highly altered by the presence of dams and that these changes generate a reduction of delivered sediments and alter the overall downstream sedimentary dynamics. Within this context, studies focusing on basins in Mediterranean regions are still scarce and, to address this shortcoming, we constructed the sediment budget of a highly regulated river, the upper River Muga (southern Pyrenees, NE Iberian Peninsula, NW Mediterranean Sea). Among the NW mesoscale Mediterranean catchments that flow directly into the sea, the Muga is one of the most altered owing to dam presence in terms of hydrology (Piqué et al., 2016). In addition to the dam, the river is affected by changes in climate and other anthropic pressures (i.e., rising water demands), making it representative of the hydrosedimentary dynamics of rivers in the region. We therefore considered to (i) construct the sediment budget of a highly regulated Mediterranean river; (ii) determine the role of the reservoir on the upper basin water and sediment dynamics; and (iii) quantify the sediment deficit downstream from the dam. In order to achieve these objectives, the study has considered obtaining the water yield and the sediment transport of the two main subcatchments draining into the reservoir and has also considered the water and sediment released from the dam. Besides flow discharge, this paper quantifies the suspended sediment transport as well as the bedload, in order to achieve a more complete evaluation of the sediment fluxes. The findings provide a detailed view of the structural physical changes that affect river dynamics below dams, producing valuable information potentially applicable for management plans in highly modified fluvial environments.

2. Study area

The River Muga is located in the NE of the Iberian Peninsula. It drains an area of 758 km^2 of the southeasternmost section of the Pyrenean and the Albera ranges (Fig. 1). The altitude of the basin varies from 1443 m asl at Montnegre (NW) to sea level at the Gulf of Roses in the Mediterranean Sea (SE). The basin belongs to the Mediterranean climate domain and displays a notable variation in temperature and precipitation. Mean annual temperature in the Empordà depression (i.e., centre of the basin) is 14.5 °C, whereas in the headwaters it varies from 11 °C to 13 °C. Mean annual precipitation shows a W-E gradient ranging from > 1100 mm in the headwaters to 600 mm at the river mouth. The river flow is regulated by the Darnius-Boadella Dam, a 61 hm^3 (i.e., 1 hm^3 = 1 × 10^6 m^3) impoundment built in 1969 to ensure water supply mostly for agricultural and urban uses in the lowlands but also to produce hydropower and for flood control. The dam was constructed at the confluence of the mainstem River Muga and its tributary Arnera (Fig. 1). For the purpose of this study, the analysis has been restricted to the upper part of the catchment (upper Muga), which includes (i) the Arnera, (ii) the Rimal, (iii) the Muga upstream from the dam (hereafter Muga$_{up}$) subbasins, and (iv) part of the basin downstream from the dam. However, the Rimal was not monitored, and therefore it is not included in the sediment budget. This tributary had a minor role in the hydrosedimentary dynamics of the basin, as the Arnera and the Muga$_{up}$ subbasins together comprise 90% of the upstream basin area. The terminology we use in the paper refers to the subbasin or to the specific sampling sites; as such, the sampling site for the Arnera subbasin is EA051, the site for the Muga$_{up}$ subbasin is EA050, and the sampling point downstream the dam is EA012 (see Fig. 1 for the exact location of these sites).

The Arnera is 60.5 km^2 and is lying on Palaeozoic granites and marls, while the Muga$_{up}$ is 84.1 km^2 and overlies Paleogene and