Science of the Total Environment 540 (2016) 133–143

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

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HIGHLIGHTS

- Suspended sediment, C and N temporal fluxes of the Ésera and Isábena have been established
- Barasona Reservoir exerts a great influence on water, sediment, C and N fluxes
- 300,000 t of sediment, 16,000 of C and 222 of N were deposited in the reservoir
- Figures would increase to 2.6×106 t of C and 35,000 t of N since reservoir was constructed

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 29 June 2015
Accepted 29 June 2015
Available online 10 August 2015

Keywords:
Suspended sediment
Carbon
Nitrogen
Temporal dynamics
Barasona Reservoir
River Ésera
Ebro basin

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

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http://dx.doi.org/10.1016/j.scitotenv.2015.06.132

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 t C 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 t C y^{-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 t N y^{-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).

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 nivo-pluvial 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