Journal of Environmental Management xxx (2016) 1–13

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Spatial and temporal dynamics of macrophyte cover in a large regulated river

A. Tena [a,*], D. Vericat [a,b], L.E. Gonzalo [a], R.J. Batalla [a,b,c]

[a] Fluvial Dynamics Research Group (RIUS), University of Lleida, Lleida, Catalonia, Spain
[b] Forest Science Centre of Catalonia, Solsona, Catalonia, Spain
[c] Catalan Institute for Water Research, H2O Building, E-17003, Girona, Catalonia, Spain

ARTICLE INFO

Article history:
Received 19 April 2016
Received in revised form
9 November 2016
Accepted 15 November 2016
Available online xxx

Keywords:
Dams
Bed stability
Water clarity
Macrophyte cover
Flushing flows
Natural floods
Fluvial restoration
River Ebro

ABSTRACT

The River Ebro basin is extensively dammed. Dams alter the geomorphological functioning of the river by altering its flow regime (e.g. reducing mean and maximum discharges), increasing bed stability (armouring) and decreasing turbidity (water clarity). These effects, together with an increase in nutrient concentrations and water temperature, have generated optimal conditions for the proliferation of aquatic macrophytes. In this paper, we analyse the temporal and spatial changes of macrophyte cover in the lowermost Ebro through a series of field campaigns carried out between 2009 and 2010. Special attention was paid to the spatial distribution of macrophytes in relation to flow hydraulics, channel geometry and bed sedimentology. Temporal changes in macrophyte cover were analysed in relation to the frequency and magnitude of both *natural* floods and flushing flows (artificial flow releases from dams with generally a magnitude that equates around a2-year flood in the river). Spatially, the proportion of macrophytes along the reaches showed a variable pattern, with a succession of areas with both high and low plant density, coinciding with the alternation of riffles and pools in the channel. The highest values of plant cover (>65%) occurred in riffles and in transition to riffle areas, while the lowest densities (1% or almost negligible) were observed in pools and transition to pool areas. Water depth and the grain-size distribution of the riverbed materials (i.e. D_{84}), are found to be the main factors controlling the degree of plant cover in the lower Ebro. Temporally, the macrophyte proportion varied during the hydrological year, with a clear increment from late spring to early autumn (i.e. vegetation cover reached 40%, on average, of the channel surface). Macrophyte coverage decreases immediately following a flushing flow but in the long term, vegetation re-occupied the area again, even slightly increasing in some sections; overall, the mean percentage of macrophyte cover was 19% higher at the end of the study period, despite the numerous flow events occurred on the meantime. This increase enhanced riverbed stability, which in turn reduced the possibility for bed-material entrainment. This study empirically confirms the necessity of improving the management options applied in the lower Ebro with complementary measures to help maximise the efficiency of flow releases (for instance, subject the macrophytes to a severe hydrological stress by decreasing discharge before a given flushing flow, undertake localise mechanical removal of plants in areas where density is high, and increase the frequency of floods in winter time when macrophyte stands are weaker).

1. Introduction

Dams interrupt the continuity of water and sediment fluxes, causing morphological and sedimentary alterations that ultimately affect river functioning (e.g. Williams and Wolman, 1984; Wilcock et al., 1996; Kondolf, 1998). The River Ebro, the longest in the Iberian Peninsula, experiences a series of adjustments in its lower reaches driven by anthropogenic impacts, both in the basin (e.g. land use changes, mostly afforestation) and in the river network itself (most notably damming). Flow regulation in the Ebro basin (ca 190 large dams in the catchment) has altered river functioning, particularly in its lower reaches, where the capacity of regulation (7700 hm^3) equates to ca. 2/3 of the annual runoff. Damming has brought a significant reduction in the magnitude and frequency of

* Corresponding author.
E-mail address: alvaro.tena@macs.udl.cat (A. Tena).

http://dx.doi.org/10.1016/j.jenvman.2016.11.034

floods, for instance reducing flood magnitude for relatively frequent events (i.e. from 2 to 20 years return period) to around 25% of natural values (Batalla et al., 2004). Total sediment load in the lowermost Ebro has also decreased during the second half of the 20th century (ca. 97–99%, Vericat and Batalla, 2006; Tena et al., 2011), when the majority of the dams were commissioned. This trend has occurred within a context of a wider natural afforestation in the basin's headwaters, a fact that reduces erosion and hence sediment delivery to the lowlands and the delta. Vericat and Batalla (2006) reported on the sediment retention rates in the lowermost reservoir complex of the lower Ebro (Mequinenza-Ribarroja-Flix Dam Complex, hereafter MRFDC). This complex traps all the bedload and a large proportion of the suspended load (>90% of the long-term average). Hydrological and sedimentary alterations lead to physical adjustments in downstream reaches, such as bed degradation (Vericat and Batalla, 2006) through cycles of river bed armouring and incision (Vericat et al., 2006) and channel narrowing due to colonization of formerly active bars by riparian vegetation (Sanz et al., 2001; Batalla et al., 2006). Although the sediment transfer downstream from MRFDC is substantially reduced, the recent studies by Tena et al., (2012) and Tena and Batalla (2013) indicate that the river's sediment load improves downstream due to occasional sediment supply from tributaries, and fine sediment supply from localised sources in the channel (e.g. bank erosion).

Post-dam environmental conditions have altered the ecological functioning of the lower Ebro. Decreases in mean and maximum discharges (Batalla et al., 2004), bed stability (Vericat et al., 2006), along with greater water clarity (i.e. low turbidity, Tena et al., 2011; Tena and Batalla, 2013), and significant increases in the nutrient concentration (Ibañez et al., 2008) and water temperature (Val et al., 2003), have generated optimal conditions for the proliferation of aquatic vegetation (see Palau et al., 2004 for a preliminary assessment and Batalla and Vericat, 2009 for a complete overview). Although several studies have reported the positive influence of macrophyte cover in river functioning (e.g. river self-purification, photosynthesis, increasing habitat complexity, Triska et al., 1989; Wilcock et al., 1999; Kemp et al., 2000; Schultz et al., 2003; Schultz and Dibble, 2012), this is not the case of the Ebro. Here, the excess of macrophytes (especially *Potamogeton pectinatus* L., *Myriophyllum spicatum* L. and *Ceratophyllum demersum* L.) causes problems associated with the clogging of water intakes of irrigation pumping stations and, particularly, the Ascó nuclear power plant located near the river, up to the point of temporarily stopping power production.

The most obvious impact of macrophytes in open channels is on flow hydraulics; i.e. increase in flow resistance (Wu et al., 1999; Nikora et al., 2008) and velocity attenuation (Dodds and Biggs, 2002). The hydraulic effects associated with excess aquatic vegetation may lead to flood management issues, as plants change wetted channel areas and so the risk of flooding may increase during high flow events (see an example on the Ebro in Prats et al., 2009). Additionally, massive macrophyte development in the lower Ebro is seen as the main cause of black-fly (*Simulium* spp.) plague that constitutes an important public-health threat for riverine populations, especially during summer months (Ibañez et al., 2008). The control of macrophytes and *Simulium* by means of chemical treatments is not permitted at a large scale because of constraints of drinking water supply and water quality preservation. Mechanical macrophyte extraction has been tested, but it requires costly labour-intensive cleaning operations that may in turn disturb water services (e.g. MacArthur et al., 2009). However, it is well known that high flows can uproot or, at least, weaken plant resistance (Riis and Biggs, 2001, 2003). In a context in which natural floods are infrequent, artificial releases from dams (i.e. Flushing Flows; hereafter FF) can be a potential solution for the Ebro. Although this kind of hydraulic practice has been used in riverine restoration programs with a variety of ecological and management objectives (e.g. Kondolf and Wilcock, 1996; Robinson and Uehlinger, 2003; Scheurer and Molinari, 2003), there are relatively few documented examples in which flushing flows have been implemented to remove macrophytes to reduce their associated undesirable environmental and societal effects (e.g. Rørslett and Johansen, 1996; Uehlinger et al., 2003; Scheurer and Molinari, 2003). In the lower Ebro, FFs have been designed and executed since 2002 in collaboration with the hydropower company Endesa SA and the supervision of the Ebro Water Authorities. Peak discharges during these events represent a recurrence interval of 2 years (a value that corresponds to a peak discharge of around 1200 $m^3 s^{-1}$ in the Ascó gauging station). The main objectives of these floods were i) to control growth and spread of macrophyte populations, and ii) to maintain a baseline of sedimentary activity in the channel (see more details in Batalla and Vericat, 2009; Tena et al., 2013). FF events have been monitored since then to assess the impact of hydraulic variation in sediment transport and macrophyte uprooting. Cost-benefit analysis of the artificial releases were also assessed and modelled by Gómez et al. (2015). Batalla and Vericat (2009) reported that in areas close to the dams, 90% of the macrophyte cover was typically removed. However, removal efficiency diminishes in both space (e.g. values at around 5% were obtained 28 km downstream) and time (i.e. a progressive reduction in the rate of macrophyte removal after has been steadily observed from 2002 to 2010). FFs in the lower Ebro became less effective as the river channel evolved and a new design adapted to the current conditions (i.e. higher peak magnitude and rate of flashiness) was therefore designed, implemented and monitored in November 2010. The information obtained through monitoring releases and their effects has been fundamental to assess the effectiveness of the new FF design and to compare it with previous designs. Within this context, the objectives of this study are: i) to describe the spatial distribution of macrophyte cover in the lower River Ebro, and determine the hydraulic and morpho-sedimentary factors that explain the observed spatial patterns; ii) to assess the temporal distribution of the aquatic vegetation in relation to the river's flow regime. Special attention is paid to the role of high flow events, especially the Flushing Flow releases, whose effectiveness in terms of macrophyte removal is evaluated over time.

2. Materials and methods

2.1. The study reach

The Ebro basin drains a total area of 85,534 km^2 (Fig. 1). The maximum altitude of the basin is in the Central Pyrenees (3404 m a.s.l.) and the minimum is at sea level in the delta. The mean annual discharge at the lowermost gauging station (i.e. Tortosa, close to the beginning of the delta plain) for the period 1912–2012 was 438 $m^3 s^{-1}$. The mean water yield was 14,060 $hm^3 y^{-1}$ (*Standard Deviation* = 4613 hm^3, i.e. 1 $hm^3 = 1 \times 10^6 m^3$), ranging from maximum of 30,821 $hm^3 y^{-1}$ recorded in the hydrological year 1914–1915 to a minimum of 4280 $hm^3 y^{-1}$ in 1989–1990. The minimum and maximum daily discharge recorded in Tortosa were 12 $m^3 s^{-1}$ and 4500 $m^3 s^{-1}$, respectively, while the maximum peak discharge estimated there attained more than 12,000 $m^3 s^{-1}$ during the 1907 historical flood (Novoa, 1984). The Ebro basin has been progressively regulated during the second half of the 20th century, especially during the period 1950–1975, when a total of 5200 hm^3 of water were impounded (2/3 of the current total reservoirs' capacity). The most important complex of reservoirs in the Ebro basin