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Reservoir impacts downstream in highly regulated river basins: the Ebro delta and the Guadalquivir estuary in Spain

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Abstract. Regulation by reservoirs affects both the freshwater regime and the sediment delivery at the area downstream, and may have a significant impact on water quality in the final transitional water bodies. Spain is one the countries with more water storage capacity by reservoirs in the world. Dense reservoir networks can be found in most of the hydrographic basins, especially in the central and southern regions. The spatial redistribution of the seasonal and annual water storage in reservoirs for irrigation and urban supply, mainly, has resulted in significant changes of water flow and sediment load regimes, together with a fostered development of soil and water uses, with environmental impacts downstream and higher vulnerability of these areas to the sea level rise and drought occurrence. This work shows these effects in the Guadalquivir and the Ebro River basins, two of the largest regulated areas in Spain. The results show a 71 % decrease of the annual freshwater input to the Guadalquivir River estuary during 1930–2014, an increase of 420 % of the irrigated area upstream the estuary, and suspended sediment loads up to 1000 % the initial levels. In the Ebro River delta, the annual water yield has decreased over a 30 % but, on the contrary, the big reservoirs are located in the main stream, and the sediment load has decreased a 99 %, resulting in a delta coastal regression up to 10 m per year and the massive presence of macrophytes in the lower river. Adaptive actions proposed to face these impacts in a sea level rise scenario are also analyzed.

1 Introduction

Highly regulated catchments can be found over the world, being Spain one of the countries with more water storage capacity. The decrease of flood events and the storage of water results in significant decreases of both the freshwater and sediment supply to the final transitional waters, with morphological, water-quality related and ecological impacts, especially enhanced by the current sea level rise. The social benefits of dam construction may be hidden by these environmental effects that finally affect the economy and the social welfare (Morris and Fan, 2000).

This work shows the current regime of freshwater flow and suspended sediments in both the Ebro and the Guadalquivir River basins, in the context of their Hydrological Plans, and some of the adaptation actions proposed at each site.

2 The Ebro River basin: current conditions

The Ebro River has a contributing area of approximately 85 900 km^2 with a total river length of 970 km. It is the biggest catchment in Spain and one of the most European regulated rivers, with three big in-stream reservoirs in the lower parts of the river, draining to the Mediterranean Sea through a deltaic formation, the Ebro Delta (Fig. 1). The basin goes through nine different regions in Spain, with different competences on water uses. The allocation of water

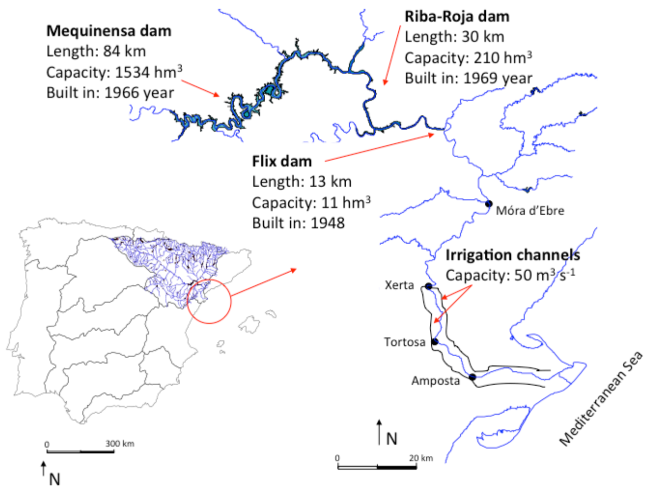

Figure 1. The Ebro River basin in Spain. Location and drainage network (left), the final reach of the river and the Ebro Delta in the Mediterranean Sea (right) with location of dams and main irrigation channels.

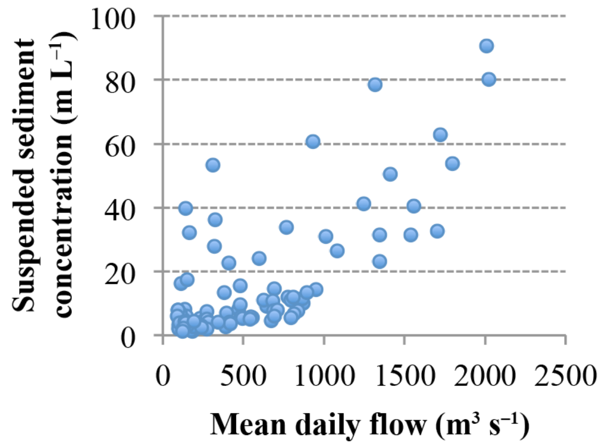

Figure 2. Rating curve of water flow-suspended sediment concentration at Tortosa (Fig. 1) in the lower Ebro River, obtained from data during March 2008–December 2015.

resources from the basin is a source of conflicts, not only due to the water uses within and upstream from each region, but also because of the established water uses recently approved by the Spanish Government in the new Ebro River Basin Plan.

The mean annual average precipitation in the catchment, with strong snow influence, ranges from over 2000 mm in the Pyrenees to less than 400 mm in the internal arid areas, with mean annual average temperature of 12.5 °C but strong local gradients across the river basin (www.chebro.es, last access: 30 January 2016). The annual runoff is highly variable as usually found in Mediterranean catchments, but it has dramatically decreased during the 20th century due to increasing water uses and the river regulation from reservoirs (Gallart and Llorens, 2004). The mean annual flow at Tortosa (Fig. 1), close to the Mediterranean Sea, for the period 1981–2010 is 289 $m^3 s^{-1}$ (Rovira et al., 2015), value well below the estimated 464 $km^3 s^{-1}$ under natural regime conditions given by the current hydrological plan (www.chebro.es). Water resources are allocated to irrigation, hydropower production, and urban uses. Up to 190 reservoirs, most of them built during the 1950–1975 period, regulate 57 % of the mean annual water yield (Batalla et al., 2004), regulate the river flow with a total impoundment capacity of 7524 hm^3 (0.088 $hm^3 km^{-2}$).

The reservoir network and the existing dams close to the delta capture most of the sediment loads from the catchment (Rovira et al., 2014), which adds to the effects of the current trend of sea level rise; both processes and the loss of freshwater delivery affect the subsidence dynamics of the delta, as many authors state (Ibáñez et al., 2010). The final in-stream system of dams formed by the Mequinensa-Ribaroja and Flix reservoirs (see Fig. 1) virtually trap all sediments transported by the Ebro River mainstream and the Segre-Cinca tributaries. In consequence, the total sediment load debouched to the Ebro delta and the Mediterranean Sea has dramatically dropped from approximately 20–30 million $t yr^{-1}$ at the end of the 19th century (Varela et al., 1986; Ibáñez et al., 1996), to 0.99 million $t yr^{-1}$ at present (Rovira et al., 2015). Figure 2 shows the relationship between the mean water discharge and suspended sediment concentration at Tortosa (Fig. 1), located approximately 40 km upstream from the delta and 15 km from the estuarine zone, obtained from daily data during 2008–2015. The values are well below the reported concentrations during floods at the beginning of the past century, which ranged between 1 and 10 $g L^{-1}$ (Gorría, 1877; Ibáñez et al., 1996).

The loss of sediment supply has resulted in a coastal regression greater than 10 m per year at the river mouth, where 150 ha of wetland were lost between 1957 and 2000. This sediment deficit is augmented by the reduction in the average elevation or height of the Delta, due to the sea level rise and the natural subsidence affecting the Delta (Ibáñez et al., 2010). Hence, around 50 % of the Delta's surface area could be under the sea level at the end of the 21st century (Alvarado-Aguilar et al., 2012). In addition, changes in the Ebro fluvial regime (i.e. annual water yield reduction, decrease on the magnitude and frequency of medium and large floods; Batalla et al., 2004), has lead to the explosion of macrophytes along the lower Ebro River (Ibáñez et al., 2012) with a tremendous ecological impact.

3 The Guadalquivir River basin: current conditions

The Guadalquivir River has a contributing catchment of approximately 57 400 km^2 and a length of 657 km. It is one of the biggest catchment in Spain and one of the most regulated, with 60 reservoirs distributed throughout the tributaries of

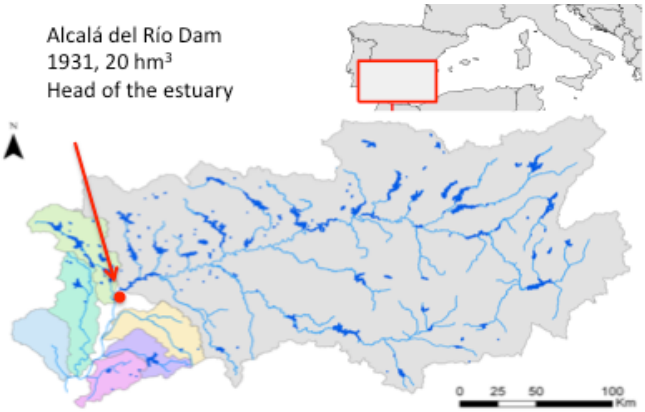

Figure 3. The Guadalquivir River basin in Spain draining to the Atlantic Ocean. Drainage network and reservoirs (dark blue small areas) upstream the estuary (grey area); the red point locates the Alcalá del Río dam, at the head of the estuary. The coloured sub-basins drain directly to the estuary area.

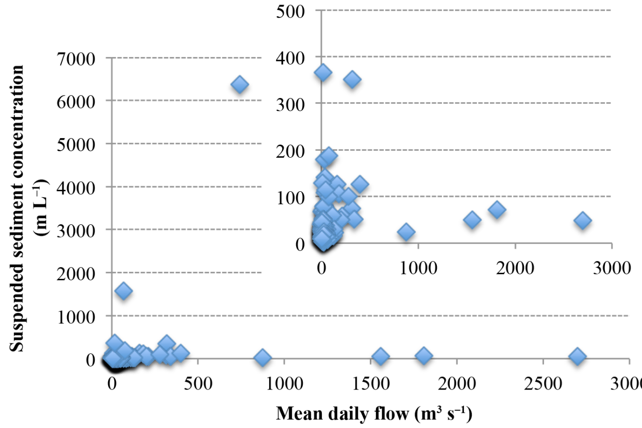

Figure 4. Rating curve water flow-suspended sediment concentration downstream the Alcalá del Río Dam (Fig. 3) in the head of the Guadalquivir Estuary, obtained from data during 1993–2007; a zoom for the interval 0–500 $\mathrm{mg\,L^{-1}}$ is included for clarity.

the river, draining to the Atlantic Ocean through an estuarine area, the Guadalquivir Estuary (Fig. 3). The basin belongs to three different regions in Spain but up to a 90 % of its area is in Andalusia, and the allocation of water resources from the basin is mainly for irrigation (80 % of the water resource volume).

The mean annual average precipitation in the catchment, with a slight snow influence at its headwaters, is higher than 2000 mm in mountainous areas throughout the basin, and lower than 300 mm in the eastern arid areas, with mean annual average temperature of 16.9 °C and strong local gradients, especially at the East, where snow and semiarid areas coexist (www.chguadalquivir.es, last access: 30 January 2016). The annual runoff is also highly variable, but its significant decrease during the 20th century is associated to the increase of irrigated areas (Contreras, 2012).

Most of the reservoirs were built during the 1930–1970 period and the 1970–1990 period (equivalent to the 50 and 75 % of the total capacity; Contreras, 2012), regulate the river flow with a global capacity of 8101 $\mathrm{hm^3}$ (0.1411 $\mathrm{hm^3\,km^{-2}}$). The mean annual flow at Alcalá del Río (Fig. 3), at the head of the estuary, was estimated as 129 $\mathrm{m^3\,s^{-1}}$ during the period 1931–1980, and as 63 $\mathrm{m^3\,s^{-1}}$ after this period (Contreras, 2012); these values, however, strongly contrast with the maximum flows during flooding periods, that reached 5400 and 6700 $\mathrm{m^3\,s^{-1}}$ in Cordoba and Seville, respectively, in February 1963 (the historical maximum during the 20th century), and reduced to values over 3000 $\mathrm{m^3\,s^{-1}}$ after the building of dams afterwards (www.chguadalquivir.es).

The high regulation per unit area in the catchment has also led to a high trapping efficiency of the sediments; however, the lack of in-stream reservoirs in the Guadalquivir River (the influence of the Alcalá del Río dam with just 20 $\mathrm{hm^3}$ is negligible) and the cropping system used downstream dams result in significant suspended sediments concentration in the river. Figure 4 shows the relationship between the mean daily flow delivered by Alcalá del Río and the suspended sediment concentration during 1993-2007.

However, significantly higher concentrations are usually found along the estuary, in which the dramatic decrease of freshwater delivery from the catchment has altered the sediment dynamics and budget, two turbidity maximum areas found (Díez-Minguito et al., 2012), and tidal dynamics influencing both salinity and sediments dynamics (Díez-Minguito et al., 2013, 2014), with turbidity events that may persist over weeks after a flooding event. Contreras and Polo (2012) reported values up to 14 and 9 $\mathrm{g\,L^{-1}}$ at the upper and medium-low reaches of the estuary.

4 Adaptation actions: some reflections

Both the Ebro Delta and the Guadalquivir Estuary suffer strong morphological changes due to the decrease of freshwater from their catchments and the trapping effect of their reservoir networks. However, despite the differences from the marine dynamics between both systems (Mediterranean Sea and Atlantic Ocean), some additional factors produce the opposite effects. In the Ebro River, the presence of in-stream reservoirs in the lower parts of the river basin results in a very low suspended-sediment concentration and a low sediment delivery to the delta. In the Guadalquivir River, the lack of reservoirs in the main stream results in high suspended-sediment concentrations along its pathway that is significantly increased in the estuary due to the very low freshwater delivery from the catchment, and the usual dominance under such conditions of the tidal processes. Figures 2 and 4 show the different order of magnitude of the current concentrations of suspended sediments in each one of both cases.

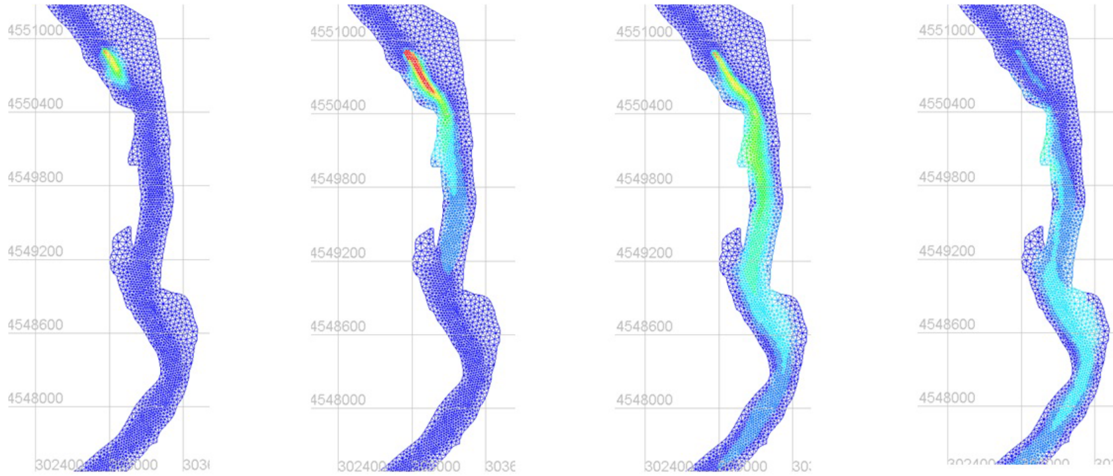

Figure 5. 2-dimensional simulation of the time evolution (from left to right) of the suspended sediment plume generated by a controlled injection at Mora d'Ebre (see Fig. 1) in the final reach of the Ebro River; permanent flow conditions of $100\,m^3\,s^{-1}$ and a triangular sedimentograph for the load with maximum value of $50\,mg\,L^{-1}$.

In the projected actions to mitigate some of the effects of the water use upstream, the Guadalquivir River Authority proposes a transfer of water from upstream Alcalá del Río to the rice farmers in the estuary, who have serious damages from the higher salinity during the medium and low water regime. Some actions are also intended for environmental objectives.

In the Ebro River, the planned water uses have recently arisen conflicts and protests from the neighboring areas of the delta and Catalonia in general. As to the dramatic sediment deficit, the on-going LIFE project, EBRO-ADMICLIM, is developing pilot actions of sediment injections in the lower reach of the river to cope with the trapping by reservoirs (http://www.lifeebroadmiclim.eu/es/, last access: 8 April 2016). Figure 5 shows one example of the simulations performed to design these injections within the project.

However, no adaptation focus is included in the hydrological plans to decrease water use in the catchments. Despite the specific processes leading to the environmental affections in both the Ebro delta and the Guadalquivir estuary, and the warming period and increasing sea level rise, undoubtedly an increase of the freshwater delivery to these systems would mitigate the imbalances and make any other action much more efficient. When will society assume the excessive consumption of water in these regions? Adaptation should be an optimal point between adapting the environment to us, and adapting us to the environment.

5 Conclusions

The work presents two highly regulated but different catchments in Spain and the main general impacts of their reservoir networks. The different type of network, with or without in-stream reservoirs, has a different impact on the sediment delivery to the river mouth. Despite their differences in the tidal dynamics, the significant decrease of freshwater suffered by both of them greatly affects the riverine, and deltaic/estuarine morphologies. Adaptation actions must foresee a decrease in the water use upstream throughout the catchment, if an efficient adaptation plan is to be developed. Specific actions such as study of the pilot injections studied in the EBRO-ADMICLIM project are needed to cope with the future conditions, and science and engineering can jointly contribute to a rigorous decision-making framework that provides support for unpopular but necessary measurements.

Author contributions. María J. Polo collected the information about the Guadalquivir River Basin, designed the experiments simulated in the Ebro River, and prepared the manuscript; A. Rovira collected the information about the Ebro River basin, carried out the field campaigns at the Ebro River and collaborated in the experimental design and manuscript redaction; D. García-Contreras adapted the model code of the Ebro River simulations and performed them; E. Contreras and C. Aguilar analyzed the Guadalquivir River data; A. Millares participated in the experimental design of the Ebro River simulations; Miguel A. Losada supervised the Guadalquivir River Basin study.

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