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Reservoir impacts downstream in highly regulated river basins: implications for IRBM and adaptive actions in the Ebro delta and the Guadalquivir estuary in Spain

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Abstract

Regulation by reservoirs affect 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. a reduction up to a 90% of the sediment delivery from the basin. In the Ebro River delta, freshwater annual input has decreased over a 30% but, on the contrary, the reservoirs are in the main stream, with an associated development of hydropower generation, and the sediment load has decreased a 99%, with a regression of the delta up to 10 m per year and the persistence of macrophyte development in the final reach of the river. Adaptive actions proposed to face these impacts in a sea level increase scenario are also analyzed.

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 increase period. The social benefits of dams 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.

The Ebro River Basin: current conditions

The Ebro River has a contributing catchment of approximately 85900 km^2 and a length of 970 km. It is the biggest catchment in Spain and one of the most regulated, with three in-stream reservoirs along the final reach of the river, draining to the Mediterranean Sea through a deltaic formation, the Ebro Delta (Fig. 1). The basin belongs to nine different regions in Spain and the allocation of water resources from the basin is source of conflicts, not only due to the water uses within each region and upstream the final delta, but also because of a water transfer to a different basin being authorized by the Spanish Government in the current hydrological planning cycle.

The mean annual average precipitation in the catchment, with strong snow influence, is higher than 2000 mm in the Pyrenees mountains and lower than 400 mm in the internal arid areas, with mean annual average temperature of 12.5C but strong local gradients (www.chebro.es). The annual runoff is highly variable as usually found in Mediterranean catchments, but it has dramatically decreased during the XXth century due to the increasing water demands (Gallart and Llorens, 2004). The mean annual flow at Tortosa (Fig. 1), close to the Mediterranean Sea, is currently 425 m^3s^{-1} (Vericat and Batalla, 2005), in contrast to the estimated 464 km^3s^{-1} under natural regime given by the current hydrological plan (www.chebro.es). Water resources are allocated to irrigation, hydro-power production, and urban uses. A total number of 187 reservoirs, most of them built during the 1950-1975 period (equivalent to the 67% of the total capacity; Vericat and Batalla, 2005), regulate the river flow with a global capacity of 7524 hm^3 (0,088 hm^3 km^{-2}).

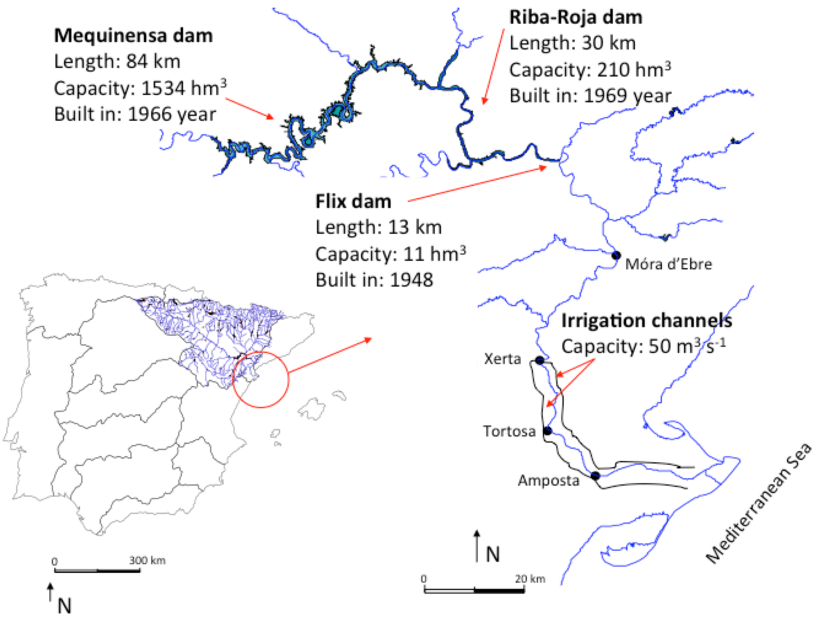

Figure 1. The Ebro River Basin in Spain. Location and drainage network (left), the final reach of the river and the Ebro Delta in the Mediterranean Sea (right) with location of dams and main irrigation channels.

The reservoir network and the existing dams close to the delta capture most of the sediment loads from the catchment (Vericat and Batalla, 2005; 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 three dams (see Fig. 1) retain the sediments from the final tributaties. The sediment retention results in a current regime of concentrations in the final reach of the river much shifted from the natural regime. As Vericat and Batalla (2005) report from other authors, the sediment contribution of the Ebro River to its delta at the beginning of the XXth century was estimated as 15.10^6 tons yr^{-1}, whereas a mean release of 263.10^3 tons yr^{-1} from the Mequinensa and Riba-Roja dams was reported by Sanz et al. (1999) (in Vericat and Batalla, 2005). Rovira et al. (2015) reported a mean value of the suspended load transferred from the river to the delta of 99,5 tons yr^{-1} during the period 1981-2010. Figure 2 shows the relationship between the mean flow and suspended sediment concentration at Tortosa (Fig. 1), close to the delta, obtained from daily data during 2008-2015. The values are well below the reported concentrations during floods at the beginning of the past century, between 1-10 g L^{-1} (Vericat and Batalla, 2005).

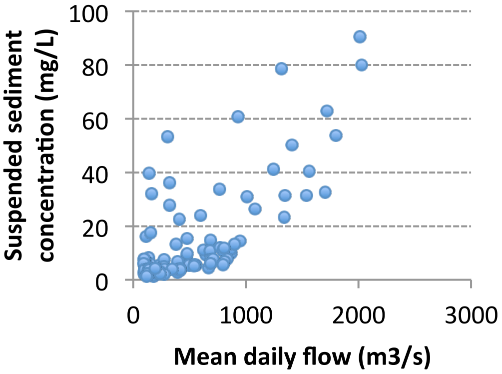

Figure 2. Rating curve water flow-suspended sediment concentration at Tortosa (Fig. 1) in the final reach of the Ebro River, obtained from data during March, 2008-December, 2015.

The loss of sediment supply has resulted in a retreat of 10 m in the delta during the last XX years, and an estimation of a 45% of the currently emerged delta surface being submerged under these conditions by the end of this century, due to subsidence and sea level rise (Ibáñez et al., 2010). Additional ecological impacts of the water flow reduction is the increased presence of macrophytes in this low reach of the river (Ibáñez et al., 2012).

The Guadalquivir River Basin: current conditions

The Guadalquivir River has a contributing catchment of approximately 57400 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 the river, draining to the Atlantic Ocean through a 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 16.9C and strong local gradients, especially at the East, where snow and semiarid areas coexist (www.chguadalquivir.es). The annual runoff is also highly variable, but its significant decrease during the XXth 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 hm^3 (0,1411 hm^3 km^{-2}). The mean annual flow at Alcalá del Río (Fig. 3), at the head of the estuary, was estimated as 129 m^3s^{-1} during the period 1931-1980, and as 63 m^3s^{-1} (Contreras, 2012); these values, however, strongly contrast with the maximum flows during flooding periods, that reached 5400 and 6700 m^3s^{-1} in Cordoba and Seville, respectively, in February 1963 (the historical maximum during the XXth century), and reduced to values over 3000 m^3s^{-1} after the building of dams afterwards (www.chguadalquivir.es).

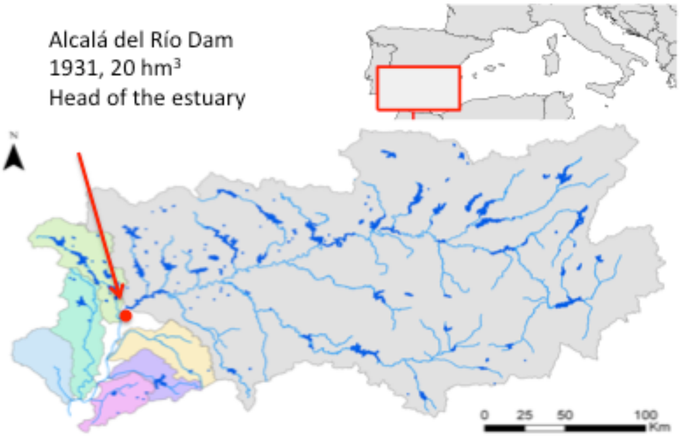

Figure 3. The Guadalquivir River Basin in Spain draining to the Atlantic Ocean. Drainage network and reservoirs (dark blue small areas) upstream the estuary (grey area); the red point locates the Alcalá del Río dam, at the head of the estuary. The coloured sub-basins drain directly to the estuary area.

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 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.

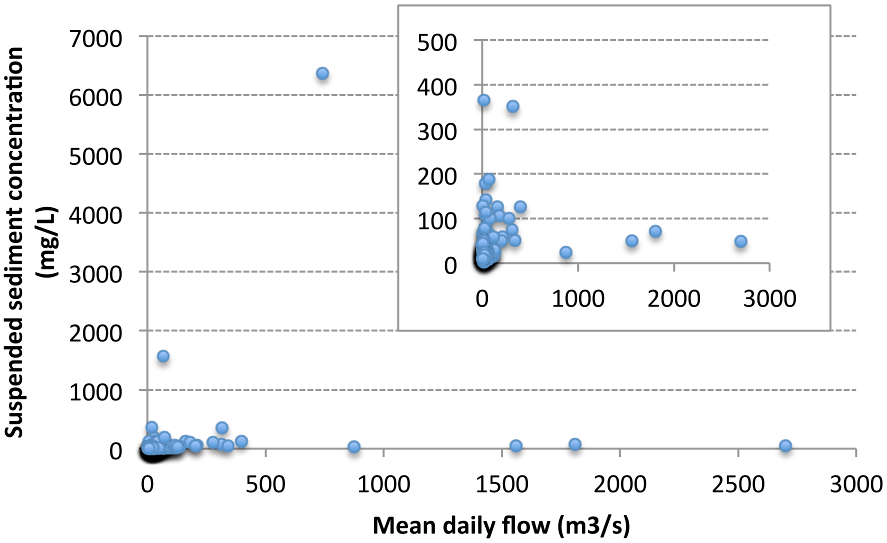

Figure 4. Rating curve water flow-suspended sediment concentration downstream the Alcalá del Río Dam (Fig. 3) in the head of the Guadalquivir Estuary, obtained from data during 1993-2007; a zoom for the interval 0-500 mg L^{-1} is included for clarity.

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 g L^{-1} at the upper and medium-low reaches of the estuary.

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 at the final reach results in a very low suspended sediment concentration and a low delivery to the delta. In the Guadalquivir River, the lack of reservoirs in the main stream results in high suspended sediments 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 both cases.

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 water transfer to other regions has recently arised conflicts and protests from the neighboring areas of the delta and Catalonia in general. As to the sediment loss, the on-going LIFE project, EBRO-ADMICLIM (http://www.lifeebroadmiclim.eu/es/) is developing pilot actions of sediment injections in the lower reach of the river to cope with the trapping by reservoirs. Figure 5 shows one example of the simulations performed to design these injections within the project.

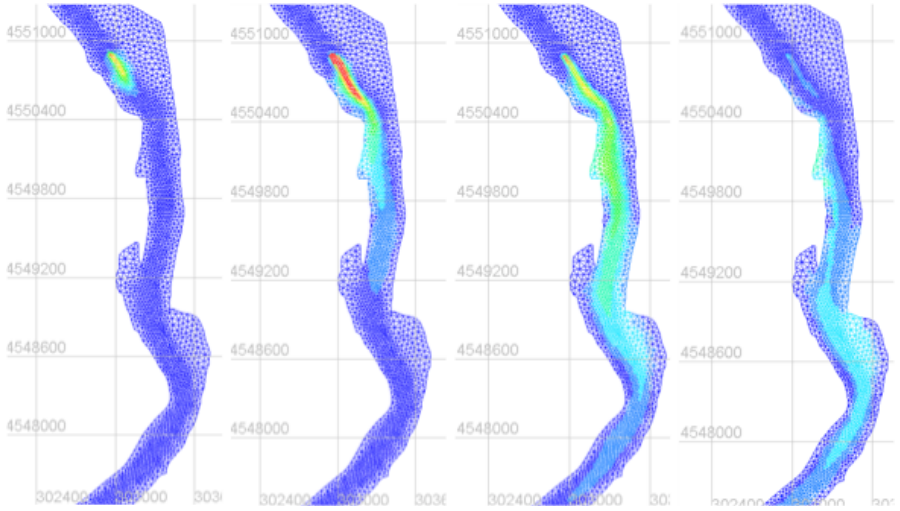

Figure 5. 2-dimensional simulation of the time evolution (from left to right) of the suspended sediment plume generated by a controlled injection at Mora d'Ebre (see Fig. 1) in the final reach of the Ebro River; permanent flow conditions of 100 m^3s^{-1} and a triangular sedimentograph for the load with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

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.

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.

Acknowledgements

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