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Biogeomorphic responses to flow regulation and fine sediment supply in Mediterranean streams (the Guadalete River, southern Spain)

M. González del Tánago [a,*], M.D. Bejarano [a], D. García de Jalón [a], J.C. Schmidt [b]

[a] E.T.S. de Ingenieros de Montes, Forestal y del Medio Natural, Universidad Politécnica de Madrid, Ciudad Universitaria, 28040 Madrid, Spain
[b] Department of Watershed Sciences, Utah State University, Logan, UT 84322-5210, USA

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SUMMARY

Geomorphic responses to damming are primarily determined by the magnitude of sediment transport and sediment supply alteration and by the resulting change in the balance between the two. The former change is caused by alterations in the flow regime that are caused by reservoir operations. Flow regime changes also affect the distribution and amount of riparian vegetation that, in turn, also may enhance geomorphic responses. The latter change is caused by sediment trapping in reservoirs and by the magnitude of sediment supply from watersheds that are downstream from the dam. We examined the bio-geomorphic responses to flow regulation along a Mediterranean stream located in an agricultural area of southern Spain where there is significant fine sediment erosion from adjacent hillsides. We measured changes in active channel width and riparian corridor features during the last fifty years, based on field work and aerial photographs surveys from 1956, 1984 and 2004. We assessed the hydrological alteration and sediment delivery trends linked to dam operation and land use changes. Channel narrowing of nearly 75% and 30% reduction in total corridor area, together with average accretion rates of 0.045 m y^{-1} and vegetation encroachment with a 305% increase of mature forest occurred between 1956 and 2004. Causal linkages were attributed to the strong reduction of peak flows and transport capacity of flows, together with land-use changes that likely promoted increased fine sediment delivery. Vegetation overgrowth favored by increased summer flows could contribute to the narrowing and aggradation processes. Our results differ from channel responses to damming in Mediterranean regions dominated by steep gradient gravel bed rivers, and highlight the relevance of topography and land-use affecting the sediment regime downstream from the dams. We argue for a more holistic approach of water resources and land-use management at the catchment scale in order to understand the synergistic effects of dams, sediment supply, and vegetation growth, and to design appropriate flow regulation schemes to cope with irrigation demands and flood risk management in Mediterranean streams.

1. Introduction

Dams and their associated reservoirs sustain many human activities (WCD, 2000), but some of these structures cause significant environmental problems and are a major threat to river biodiversity (Bunn and Arthington, 2002; Nilsson et al., 2005; Poff et al., 2007; Palmer et al., 2008). In the Mediterranean region of Europe, dams and reservoirs provide water supply for municipal, industrial, and agricultural uses during the annual dry period and sustain human activities in years when winter rainfall is relatively low (Kondolf and Batalla, 2005; Hooke, 2006; Grantham et al., 2010). Unfortunately, dams and reservoirs in this region compromise the ecological status and potential for ecological recovery of many river systems (Grindlay et al., 2011; González del Tánago et al., 2012). In Spain, dams and reservoirs are considered the primary cause of water body modification in the context of implementation of the European Water Framework Directive (EC, 2000; García de Jalón, 2003; Lorenzo-Lacruz et al., 2012), and reoperation of dams and evaluation of the impacts of reservoirs is a significant focus of most River Basin Management Plans (http://www.magrama.gob.es/es/agua/temas/planificacion-hidrologica/planificacion-hidrologica/planes-cuenca/).

A substantial literature describes the general ecological and geomorphic responses to large dams (Williams and Wolman, 1984; Brandt, 2000; Grant et al., 2003; Graf, 2006; Schmidt and Wilcock, 2008; Poff and Zimmerman, 2010; Grant, 2012), but the local-scale downstream effects of these structures mostly depends

* Corresponding author. Tel.: +34 91 336 6394; fax: +34 91 543 9557.
E-mail address: marta.gtanago@upm.es (M. González del Tánago).

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on geology (Grant et al., 2003), land use (Gordon and Meentemeyer, 2006), and rules of reservoir operation. Apart from altering the stream-flow regime (Poff et al., 2007), dams and reservoirs alter the downstream sediment transport regime by (i) trapping sediments and (ii) reducing the sediment transport capacity of downstream regulated flows. Downstream geomorphic and ecological effects of dams are largely determined by the relative changes in these two attributes of the sediment transport regime (Schmidt and Wilcock, 2008). Sediment deficit and channel incision associated with the trapping effects of reservoirs have been reported by many authors (Kondolf, 1997; Rinaldi and Simon, 1998; Surian and Rinaldi, 2004; Vericat and Batalla, 2006; Schmidt and Wilcock, 2008; Tena et al., 2011). In contrast, sediment surplus and channel aggradation associated with reduced transport capacity of regulated flows (e.g. Everitt, 1993; Gaeuman et al., 2005; Dean and Schmidt, 2011) has been much less well documented. Variability in response is contextual, reflecting factors such as controls upon sediment yield associated with the availability of sediment from hillslopes or tributary systems. Collectively, these considerations determine the pattern of hydrologic alteration and the balance between sediment supply and transport capacity along the regulated river system, thereby fashioning the nature and rate of channel adjustments (Schmidt and Wilcock, 2008; Burke et al., 2009).

The relative lengths of regulated rivers perturbed into deficit or surplus are dependent on factors such as location of downstream tributaries and the amount of sediment those tributaries supply to the regulated river (Reid et al., 2013). Riparian vegetation also plays an important role in determining river responses to damming, impacting various feedback processes by trapping sediments and reducing flow energy, thereby modifying process-form interactions in river systems (Corenblit et al., 2007; Dean and Schmidt, 2011; Gurnell et al., 2012). Camporeale et al. (2013) recently reviewed the interactions between riparian vegetation and river morphodynamics and provided a quantitative approach to modeling these interactions. In turn, river damming and flow regulation impact riparian vegetation to a great extent, both in terms of accelerating the rate of narrowing and affecting the total biomass of the post-regulation vegetation community (Tealdi et al., 2011). Thus, there may be different effects of dams in different physiographic and climate zones.

In Mediterranean regions, depending on geology and historical land use (i.e., traditional deforestation for grain, olive and grape farming), sediment yields to river channels may be relatively high (García Ruiz, 2010). While the consequences of agriculture development for soil erosion have been extensively reported (e.g., García Ruiz, 2010; de Graaff et al., 2010; Cantón et al., 2011), relatively little attention has been given to exploring the hydrogeomorphic impacts of agricultural practices in river systems, including the encouragement of flow regulation by dams and reservoirs for irrigation purposes and the delivery of fine sediment to river channels from soil erosion in agricultural fields.

This paper illustrates the nature of the perturbations caused by dams and reservoirs in southwestern-most Europe. The catchment is located in a highly erodible region of Andalusia, Spain, and is extensively farmed. Our objective was to explore the synergies among regulated stream flow, fine-sediment supply from eroding hill slopes, and riparian vegetation growth in the Guadalete River, where significant channel narrowing and vegetation encroachment have been observed in recent decades in response to an intensive flow regulation scheme for irrigation. The Andalusian Water Authority (i.e., Agencia Andaluza del Agua, Junta de Andalucía) is currently investing funds to remove riparian vegetation and accumulated fine sediment from the banks and floodplain of this river to increase conveyance capacity and reduce flood risk. Our research attempted to analyze the different ways in which perturbations induced by river damming differ relative to other parts of the Mediterranean region (e.g., Liébault and Piégay, 2002; Pont et al., 2009).

2. Study area

The Guadalete River is located in the southwestern part of the Iberian Peninsula and flows into the Atlantic Ocean at Cádiz Bay (Fig. 1). It drains 3360 km^2, and the river is 159 km long. The main tributary of the Guadalete River is the Majaceite River, which joins the main stem at Las Juntas. Both rivers are regulated by large dams (Table 1). Our study area was 65 km of the middle and downstream parts of the Guadalete River between Arcos Dam and the city of Jerez de la Frontera. Along this length, the river flows in a partly confined valley with a wandering or meandering planform. The bed material is gravel and sand upstream from Las Juntas where the channel slope is approximately 0.0015; the bed is primarily silty clay further downstream where the channel slope is 0.0006.

The catchment has a Mediterranean climate, with annual precipitation between 500 and 700 mm and an average annual temperature of 18 °C (http://aemet.es). Rainfall intensity may be very high, and the 100-year recurrence, 24-h duration rainfall is between 100 and 200 mm (MMARM, 2008). The basin is primarily underlain by early and middle Miocene marls and Jurassic–Tertiary limestones and marls; Quaternary gravels and sands occur in and along the alluvial valley (Moral-Cardona et al., 1995). The watershed topography is hilly, and slope gradients sometimes exceed 10%. Land cover is predominantly agriculture (i.e., olive trees, vinyards, cotton), occupying 63% of the area; Mediterranean forest stands are present in the steeper gradient slopes and comprise 35% of the basin (CORINE, 2006). Agricultural practices of much of the watershed are traditional; plowing frequently does not follow topographic contours, and bare ground is maintained under individual trees in most olive orchards. High erosion rates result. Predicted rainfall-induced soil erosion rates are between 25 and 100 t ha^{-1} y^{-1} (MMARM, 2008). Erosion rates of tributary watersheds downstream from Arcos Dam are even greater, and the highest soil losses and sediment delivery rates are in the Salado de Espera and Salado de Paterna catchments (Fig. 1) where sheet and rill erosion rates are between 100 and 200 t ha^{-1} y^{-1} (MMARM, 2008).

The Guadalete River has a Mediterranean flow regime, with pronounced seasonal variability between the wet season (i.e., from November to April) and the driest months of July and August when the discharge may be very low or nearly zero in some years. Average annual mean daily flows of the Guadalete River are approximately 5.8 m^3 s^{-1} at Bornos Dam and 10.5 m^3 s^{-1} at Las Juntas, downstream from the Majaceite River. Extraordinary peak flows have occurred in the past, with values at Bornos of 1100 m^3 s^{-1} in June 1930; 1400 m^3 s^{-1} in February 1963; and 1260 m^3 s^{-1} in January 1970; maximum discharges at Guadalcacín location on the Majaceite River were 915 m^3 s^{-1} in June 1930 and 700 m^3 s^{-1} in February 1963 (http://www.entornoajerez.com/2010/02/algunas-avenidas-e-inundaciones.html).

The stage of winter floods since 2010 has been unusually high and has inundated a vast area around Jerez de la Frontera. These floods were caused by intense winter precipitation, but discharge data are not available. In response to these floods, the Agencia Andaluza del Agua is trying to increase the conveyance capacity of the Guadalete River by removing sediments (more than 30,000 m^3) and exotic *Eucalyptus* stands (2000 individuals) from the main channel and floodplain. These *Eucalyptus* stands have been progressively invading the Guadalete corridor, together with native riparian forest dominated by *Populus alba* L., *Tamarix africana* Poir. and several *Salix* species (*S. fragilis* L., *S. pupurea* L. and *S. atrocinerea* Brot.). During the 1950s, *Eucalyptus camaldulensis*