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Reducing river regulation effects on riparian vegetation using flushing flow regimes

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ABSTRACT

One of the most salient causes of the degradation of freshwater systems is the physical habitat changes attributed to river damming. Environmental flows reduce such degradation but are still generally based on the requirements of aquatic species and disregard other biotic components of the ecosystem, such as riparian vegetation. Nevertheless, when environmental flow methods claim to consider riparian vegetation habitats and propose specific flows, their outcomes are rarely predicted quantitatively prior to their implementation. We used a dynamic floodplain vegetation model to analyze the riparian patch dynamics predicted for different flow regimes in two river stretches and to assess vegetation requirements to ensure long-term ecological maintenance and vitality of riparian structure in rivers with altered flow regimes. Furthermore, we assessed the capability of flushing flows to restore and manage riparian vegetation and the efficiency of environmental flows to satisfy riparian vegetation requirements. We found that vegetation encroachment is mainly prevented by floods with a recurrence interval of at least 2 years but that environmental flow regime planning aimed at complying with riparian vegetation requirements is watershed-specific. Additionally, reservoir flows controlled vegetation encroachment without causing severe geomorphic impacts on downstream river channels and with minor water losses to dam managers.

1. Introduction

Dams are built to retain water for human needs. However, dams also create environmental consequences, such as ecological responses to instream and riparian species proportional to the alteration of flow regime (Poff and Zimmerman, 2010). Additionally, modifications in river flow regimes are expected to increase due to increased water withdrawals to satisfy human need (Alcamo et al., 2007; Vörösmarty et al., 2010; Murray et al., 2012), and freshwater systems will endure greater biodiversity losses than other ecosystems, particularly Mediterranean ecosystems (Sala et al., 2000). The contradictory urge to protect river environments while satisfying human water demand remains one of the most important challenges of our time (Nilsson and Berggren, 2000; Palmer, 2010). Environmental flow management has been an ongoing scientific issue for the last two decades (e.g., Arthinghton and Zalucki, 1998; Acreman and Dunbar, 1999; Dyson et al., 2003; Hughes and Rood, 2003; King et al., 2003; Rood et al., 2005; King and Brown, 2006; Poff et al., 2010), prompting the use of an extensive number of methods to determine environmental flow. The most advanced methods for determining environmental flow requirements maintain biological community functions and riverine processes while focusing on flow regime over space and temporal scales. Nevertheless, these methods are generally based on the requirements of aquatic species, mostly fish (Acreman et al., 2009), and usually disregard other biotic and abiotic components. Such approaches set aside the inter-annual flow variability that rules longer lifecycles, bypassing an important aspect in river management: the long-term perspective of the riverine ecosystem (Stromberg et al., 2010).

Riparian species and communities are suitable environmental change indicators (Nilsson and Berggren, 2000; Rodríguez-González et al., 2014) and should be considered in the development of environmental flow regimes. The succession dynamics of riparian vegetation is a medium- to long-term active process that responds directly to flow regime and its disturbance (Junk et al.,

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1989; Poff et al., 1997; Richter et al., 1997; Toner and Keddy, 1997; Mallik and Richardson, 2009). Furthermore, riparian vegetation is important in aquatic habitat improvement (Naiman and Décamps, 1997; Naiman et al., 2005; Ghermandi et al., 2009) and biological conservation (Broadmeadow and Nisbet, 2004; Van Looy et al., 2013).

Several studies describe the response of riparian vegetation to flow regime changes (e.g., Greet et al., 2011a,b; Johnson and Waller, 2012; Angus Webb et al., 2013; Miller et al., 2013). However, few studies have used a spatially detailed approach to riparian patches to examine the responses of riparian vegetation (e.g., Egger et al., 2012; Benjankar et al., 2012; García-Arias et al., 2013; Rivaes et al., 2013). These cause-and-effect relationships between flow regime and riparian vegetation have seldom been used in regulated river management (e.g., to prevent vegetation encroachment and maintain sustainable riparian landscapes). These cause-and-effect relationships are important in Mediterranean climates where the downstream flow regulation of dams is acute and widespread and where hydrologic-driven changes on vegetation are most likely stronger because flow regulation persists for longer river stretches downstream of dams (Bejarano and Sordo-Ward, 2011). Additionally, as a result of regulation, base flows may increase and provide water throughout the growing season (i.e., reversing the natural flow regime), favoring the development of later successional vegetation stages and ultimately reducing biodiversity (Magdaleno and Fernández, 2010).

Reservoir outflows, in the form of flushing flows, are intended to mimic the effects of natural flows toward the removal of fine sediment and channel maintenance (Kondolf, 1998), encompassing the scour of undesired vegetation (Milhous, 2012), which is of great importance to channel flow conveyance. Methods with pre-defined flushing flows concerning this matter recommend discharges ranging from a certain percentage of the mean annual flow up to floods with a recurrence interval of 10–15 years. However, the majority of methods focus only on the sediment transport capacity of these flows, whereas rejuvenation of the riparian patch mosaic has been poorly analyzed.

This study simulated the riparian vegetation response to flow regime management to (i) determine the riparian vegetation response to different flushing flows and define which regime would be able to re-establish riparian patch dynamics, (ii) evaluate the possibility of reducing the effects of flow regulation on riparian vegetation downstream of dams through reservoir management, (iii) assess the potential damage of releasing sediment-deprived flushing flows on fluvial geomorphology, and (iv) analyze the adequacy of existing general environmental flow guidelines for riparian vegetation.

2. Materials and methods

2.1. Study sites

Two study sites ("Monte da Rocha" and "Odelouca") were used to assess vegetation response to regulated flow regimes. The Monte da Rocha study site is located in southern Portugal (Lat. 37°44′11,75″N, Long. 8°18′04,23″W) near Panóias village, on the headwaters of the Sado River. Its flow is regulated by the Monte da Rocha dam, located approximately 1 km upstream. The Monte da Rocha dam is a 40-year-old irrigation infrastructure without any intentional flow release. Nonetheless, there is permanent low flow at the study site derived from the percolation through the dam body and foundation, which slightly increases during the crop irrigation period due to the operation of the pumping station. The riparian woody vegetation in the area is largely composed of willows (*Salix atrocinerea* Brot.), ashes (*Fraxinus angustifolia* Vahl) and tamarisks (*Tamarix africana* Poir). The characteristic terrestrial species in the uplands are cork oaks (*Quercus suber* L.) and holm oaks (*Quercus ilex* L. subsp. *ballota*).

The Odelouca study site is located a little further south (Lat: 37°23′05,00″N, Long: 8°18′39,46″W) in the upper course of the Odelouca River, upstream of the Odelouca Reservoir. The river here is free-flowing, and its riparian vegetation is close to natural. The flow regime is typically Mediterranean, having two distinct periods: the winter period, with low flows that are sporadically interrupted by flash floods, and the summer period, with very low or even null flows. This river stretch was selected as the best available site with near natural conditions in terms of riparian vegetation and is representative of the downstream Odelouca River. The composition of riparian vegetation here is similar to the first study site, with willows, tamarisks and ashes being the most common woody species (Fig. 1).

2.2. Vegetation model

We used the dynamic floodplain vegetation model CASiMiR-vegetation (Benjankar et al., 2011) to determine the expected response of riparian vegetation communities to flow regime changes. This is a physically based numerical model that includes empirical relationships between relevant hydrological characteristics (Poff et al., 1997) and the riparian guild level responses to permanent hydrologic regime changes (Merritt et al., 2010). Its outputs are spatially explicit vegetation maps of the riparian vegetation patches by succession phase. The CASiMiR-vegetation model has been used to examine Mediterranean climate conditions with good results, including one of the study sites presented in this study (see García-Arias et al., 2013; Rivaes et al., 2013 for model structure, calibration and performance).

2.3. Input data

2.3.1. Hydrological and meteorological data

Hydrological and meteorological data were obtained from the National Water Resources Information System (SNIRH, 2010) and were used to create different input flow regimes for the riparian vegetation modeling. The natural flow regime at Monte da Rocha was estimated from hourly precipitation records obtained on several meteorological stations located in the drainage basin and nearby. Based on these data, natural maximum discharges at the study site were obtained for each year from the recorded precipitation using the USA Soil Conservation Service (SCS) unit hydrograph method (SCS, 1972). Peak discharges corresponding to specific recurrence periods were estimated according to the local corresponding IDF (intensity–duration–frequency) curves (Brandão et al., 2001).

We used data for the Odelouca case study from a nearby gauging station (Monte dos Pachecos) to estimate site-specific maximum instantaneous discharges for different probabilities of exceedance. The annual maximum discharges at the study site were calculated considering the ratio between "Monte dos Pachecos" and the study site drainage basin areas and their mean annual precipitation.

2.3.2. Flow regime definition

Initially, three different flow regimes were considered for vegetation modeling: dam-operated, natural and pre-defined environmental flow (hereafter called Eflow) regimes (Table 1). The dam-operated flow regime is applicable to the Monte da Rocha study site and considers the regulated flow regime below the dam over the past decade. The dam-operated flow regime was used to produce a riparian vegetation map for the actual regulated river, thus enabling model calibration by comparing with the present vegetation patches. The calibrated model was used to produce