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Modeling riparian woods and fish species: a holistic approach for environmental flows to be used on river management and conservation

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Abstract

River regulation is a global phenomenon and will intensify due to increased water demand and climate change. Flow restoration is required from water managers but a robust tool does not exist yet for Mediterranean rivers. This thesis aims to develop a holistic approach to determine environmental flows with a long-term perspective of the fluvial system incorporating both intra-annual and inter-annual hydrological variability. Results will be discussed in terms of their applicability to water management.

Keywords: Environmental flows, river restoration, riparian vegetation, climate change, flow-ecology relationships, ecosystem interactions

Introduction, scope and main objectives

On the latest review on ecological responses to altered flow regimes, Poff & Zimmerman, 2010, showed that natural flow modification have a dramatic effect both on aquatic and riparian species, especially changes in the magnitude of flow rates, often by flow stabilization. River regulation is however a global phenomenon (Arthinghton et al., 2006), and bound to increase with climate change (Palmer et al., 2008).

We need to restore environmental flows planet-wide but as societal demand for water increases we also need guidelines for managing reservoir outflows and water abstractions (Poff et al., 1997; Hughes & Rood, 2003). Lately, flow restoration became compulsory for European managers, as the Water-Framework Directive aims to achieve good ecological status in all water bodies, with a hydrologic regime capable of sustaining biological elements and river processes (Acreman & Ferguson, 2010).

The assessment of ecological flows currently uses minimum needs, implemented as a minimum constant flow of the river or as a percentage of the natural hydrological regime (Poff et al., 2010). Eco-hydraulic modeling aims at instream species requirements, but few species are usually used, mostly fish (Poff et al., 1997; Annear et al., 2002). In Portugal, flow requirements are based in empirical thresholds over the natural hydrological variability, and in a few cases in eco-hydraulic habitat simulations (Alves et al., 2003). Results have not been validated and are often questioned by conservationists and water managers.

Riparian vegetation ensures the liaison between the river channel and terrestrial ecosystems. The flow regime is the most relevant factor shaping it (Toner & Keddy, 1997). The interaction between fluvial geomorphic processes and riparian vegetation dynamics can be traced on the topographic diversity, soil moisture gradients and fluvial disturbance patches (Bornette et al., 1998). Dynamic vegetation models are particularly interesting because they consider ecologically relevant elements such as magnitude, frequency, rate of change, inter-annual variability and sequencing of flows (Rood et al., 2005) to simulate alterations of vegetation features, such as stand age and the relative proportion of the succession phases (Merritt et al., 2010).

Flow variability determines instream habitat patches, structuring river biota and year-round biological activities, such as areas available for spawning, food resources availability or prey-predator encounters. Fish habitat requirements are currently used to determine instream flow needs for different life-history stages. More recently, 2D habitat models became a powerful tool used to simulate hydraulic patterns and species habitat suitability (Santos & Ferreira, 2008). We can also determine periods when habitat conditions are under a given threshold (Parasiewicz, 2007), highly adequate for strong variability seasonal (Shafroth et al., 2010).

Yet, environmental flows definition should consider different biological communities and use the response of these to the water regime elements, including magnitude, frequency, duration, timing and flashiness (Poff et al., 1997; Acreman & Ferguson, 2010). The Building Block Methodology approaches this holistic concept (King & Louw, 1998) but is mostly based on multi-expert-judgment, while numerically robust techniques should be used, especially in European rivers where flow and biological information is becoming less empirical (Hughes & Rood, 2003).

This study aims to develop a holistic approach to determine environmental flows in lowland Mediterranean rivers, based on woody riparian vegetation and key fish species, able to recreate the typical intra-annual hydrological variability, whilst incorporating the inter-annual flow variation.

This approach will combine two predictive models: 1) a dynamic vegetation model using riparian woody patches (having extended biological cycles) as surrogates for long-term flow variability (hence, the maintenance of flushing flows, of lateral, longitudinal and vertical water connectivity, natural channel morphology and habitat disturbance), and 2) physical habitat simulations using target fish species to predict low flow needs (hence, the maintenance of shorter life cycles, including recruitment, feeding and sheltering).

So far, such an attempt encompassing biotic, hydrological and hydraulic features and different time scales has not occurred in Iberian rivers, or in lowland systems anywhere. Such a combined model would be a valuable tool for river conservation and water management, as it would predict the response of the river system to human changes, including reservoir-regulated flows, WFD's rehabilitation schemes or climatic changes.

Specifically, the objectives of this thesis are: to develop and calibrate a dynamic vegetation model based on the predictive relationship between differently-aged woody patches existing on the riverbed and the annual flow variation (relationship determined by multi-year extreme flow conditions); to assess the main drivers of the riparian vegetation's ecological succession and evaluate its relative influence towards the determination of riparian vegetation flow regime requirements; to approach riparian vegetation restoration measures by flow regime management; to determine the habitat needs for native target fish species from lowland rivers, in key-periods within a year, using habitat preference curves and a 2D-model for habitat simulation; to assess the ecological feedbacks of riparian vegetation management on aquatic communities; to combine the information of the two models in a holistic frame for environmental flows; to set reference conditions for environmental flows; to test and validate the approach in river reaches presenting different types of flow regulation and, to predict structural and functional changes of river communities affected by long-term flow changes.

Methodology/approach

Development and calibration of a dynamic riparian vegetation model

The riparian vegetation modelling presented in this thesis will be performed using CASiMiR-vegetation model. This tool recreates the physical processes influencing the survival and recruitment of riparian woody vegetation, resulting in a temporal (age) and spatial (area) riparian vegetation representation. The physical processes are modeled by zones (riparian patches in aquatic, bank and floodplain zones), each one with different calibration parameters.

Calibration will be achieved for Mediterranean rivers based on the analysis of different study sites with noticeable Mediterranean flow regime.

Calibration is made by running the model for the last ten years and comparing the result with the succession phases observed at the study sites. Classification accuracy is evaluated comparing observed versus expected succession phases with Cohen's Kappa and other model accuracy statistics.

Evaluate the influence of the riparian vegetation's ecological succession main drivers and assess the riparian vegetation flow regime requirements

The ecological succession of riparian vegetation is driven by both large and small scale drivers where the former are expected to influence riparian vegetation on a landscape dimension while the latter will likely have particular influence on a patch extension. The influence of these drivers will be assessed and tentatively quantified using the most recent statistical approaches in order to better understand those relations. This task will be supported by the existing large sampled data in the diverse study sites used in this thesis, both national and internationally, using information of riparian communities located in Portugal, Spain, Austria and Brasil, encompassing the different watershed alimentation forms that characterize the generality of river flow regimes worldwide and characteristic of different climates. In this chapter, the influence of global climate change will also be considered to foresee the expected changes of the large scale drivers in future.

Approach riparian vegetation restoration measures by flow regime management

Based on the riparian flow regime requirements determined previously, different scenarios of flow regulation will be tested to determine the best management procedure towards the restoration of the riparian communities in regulated rivers. This issue will be addressed by riparian vegetation modeling using CASiMiR-vegetation model to determine the effect of different proposed flow regimes on the reduction of the river regulation effects on riparian vegetation, benchmarked by the natural reference condition.

Using Mediterranean key-species to determine habitat needs for native target fish species

Habitat Suitability Curves of depth, velocity, substrate and instream cover will be developed for different size-classes (juveniles and adults) of fish key-species, for different seasons (methods in Santos & Ferreira, 2008), indicating respectively recruitment requirements and low-flow stressful conditions.

River2D will model the area of fish habitat used by the different life-history stages, computed as the product of depth, velocity and cover suitability indexes, according to natural discharges expected in the simulated period on the study site. Continuous under threshold habitat duration curves (Parasiewicz, 2007) will be developed to determine minimal flows required for the species.

Assess the ecological feedbacks of riparian vegetation management on aquatic communities

Using the knowledge generated during the previous tasks, particularly the flow regime and habitat requirements of both aquatic and riparian communities, this task consists in evaluate the repercussions of riparian vegetation management on the aquatic communities. This will allow understanding how the management and consequently the improvement of the riparian habitat will influence the local aquatic species. Using different scenarios of riparian landscapes, derived from different flow regime management scenarios, as matrix for the habitat characteristics inputted into the hydrodynamic modelling of fish species, the provided habitat availability of aquatic species will be determined according to each management suggestion. Furthermore, flow-ecology response curves of riparian and aquatic communities will be built and the influence of the former in the latter will be assessed.

Development of a holistic frame for environmental flows applicable to Mediterranean lowland rivers

Using the previous modeling approaches, minimal flow requirements will be determined to maintain both natural riparian patchiness in the floodplain and instream habitat, considering the life-cycles of the woody species and fish as surrogates of river functioning. When combined, they incorporate the essential aspects of natural flow variability. The approach relates to the Building Blocks Methodology but instead of expert-judgment, it incorporates calibrated biological responses that can be validated with empirical biological data from regulated reaches. For each river, a histogram with monthly environmental flows can be build for multiannual period, using minimum requirements obtained for riparian vegetation and fish habitat.

Setting reference conditions for environmental flows

Most lowland rivers have been physically altered, including channel structure and flow variability. Yet, the Water Framework Directive (WFD) requires that restoration of these rivers should be benchmarked by their approximate natural conditions, for which no true scientific solution has been achieved. Using the models developed, we will attempt to recreate natural floodplain conditions to be used as the biological and physical reference conditions for ecological status assessment and restoration guidelines (Acreman & Ferguson, 2010).

Application and validation of the approach in regulated rivers

The approach developed will be tested and validated in regulated rivers, including two types of flow regulation: storage of high flows and hydropeaking. For testing purposes, the regulated studied reaches should have minimum disturbance from other human pressures, e.g. pollution. Results will be discussed concerning guidelines for reservoirs outflow management and natural flow restoration under WFD (Acreman et al., 2009).

Preliminary results

Development and calibration of a dynamic riparian vegetation model

The CASiMiR-vegetation model was successfully calibrated for Mediterranean rivers achieving in several study sites a quadratic weighted kappa ranging from 0.61 to 0.69 when observed as proportion of maximum possible given the observed marginal frequencies.

Evaluate the influence of the riparian vegetation's ecological succession main drivers and assess the riparian vegetation flow regime requirements

The seasonality and variability of rainfall are accounted as major drivers of riparian vegetation's ecological succession. This driver influence was assessed by comparison of the existing riparian landscapes governed by the actual rainfall patterns and the expected ones ruled by future climate change scenarios. The intensification of heavy rain events during winter along with longer and harsher droughts during summer will determine the outwards expansion of non-woody sparsely vegetated areas and the inwards expansion of mature succession patches, while promoting the disappearance of intermediate pioneer and young succession stages of riparian woodlands.

Approach riparian vegetation restoration measures by flow regime management

The CASiMiR-vegetation model was used to analyze the riparian patch dynamics predicted for different flow regimes in two river stretches, as well as 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 on restoring and managing riparian vegetation and the efficiency of environmental flows to satisfy the riparian vegetation requirements. This research evidenced that vegetation encroachment is mainly prevented by floods with a recurrence interval of at least 2 years but environmental flow regime planning to comply with riparian vegetation requirements is watershed-specific. Additionally, reservoir flows were able to control vegetation encroachment without causing severe geomorphic impacts on downstream river channels and with minor water losses to dam managers.

Assess the ecological feedbacks of riparian vegetation management on aquatic communities

This study addressed this concern by evaluating the effects of environmental flow regimes disregarding riparian vegetation in the long-term perspective of the fluvial ecosystem. To achieve that purpose, the riparian vegetation evolution was modeled considering its structural response to a decade of different environmental flows, and the fish habitat availability was assessed for each of the resulting riparian habitat scenarios. We demonstrate that fish habitat availability changes accordingly to the long-term structural adjustments that riparian habitat endure following river regulation and that riparian vegetation requirements must be considered on environmental flows to assure the effectiveness of those in the long-term perspective of the fluvial ecosystem.

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