# USING CASIMIR-VEGETATION MODEL IN THE CONTEXT OF MODELING RIPARIAN WOODS AND FISH SPECIES TO SUPPORT A HOLISTIC APPROACH FOR ENVIRONMENTAL FLOWS TO BE USED ON RIVER MANAGEMENT AND CONSERVATION

# O USO DO MODELO CASIMIR-VEGETATION NO CONTEXTO DA MODELAÇÃO DE BOSQUES RIPÁRIOS E ESPÉCIES PISCÍCOLAS PARA SUPORTE A UMA ABORDAGEM HOLÍSTICA DE CAUDAIS AMBIENTAIS A USAR NA CONSERVAÇÃO E GESTÃO FLUVIAIS

**Rui Pedro Rivaes**
Doutorando em Restauro e Gestão Fluviais (FLUVIO) / ISA, Universidade de Lisboa – (ruirivaes@netcabo.pt)

**António Nascimento Pinheiro**
Doutor em Engenharia Civil / IST, Universidade de Lisboa. Professor Catedrático do Departamento de Engenharia Civil, Arquitectura e Georrecursos do Instituto Superior Técnico, Universidade de Lisboa. – (antonio.pinheiro@tecnico.ulisboa.pt)

**Gregory Egger**
Doutor em Gestão Fluvial e Ecologia de Vegetação / University of Natural Resources and Applied Life Sciences - Áustria. Professor interino em ecologia fluvial e de planícies de inundação no Institute of Floodplain Ecology, University Karlsruhe - Alemanha. (gregory.egger@kit.edu)

**Maria Teresa Ferreira**
Doutora em Engenharia Florestal / ISA, Universidade de Lisboa. Professora Catedrática do Departamento de Recursos Naturais, Ambiente e Território do Instituto Superior de Agronomia, Universidade de Lisboa. (terferreira@isa.ulisboa.pt)

## Resumo
O modelo CASiMiR-vegetation recria os processos físicos que influenciam a sobrevivência e recrutamento da vegetação ripária, baseando-se na relação entre componentes do regime hidrológico ecologicamente relevantes e métricas de vegetação que refletem a resposta às alterações do regime hidrológico. Trabalhando ao nível da guilda de resposta ao escoamento, esta ferramenta supera modelos equivalentes ultrapassando várias restrições presentes nas modelações convencionais. O potencial do modelo CASiMiR-vegetation é revelado na sua aplicação a diferentes casos de estudo durante o desenvolvimento de uma abordagem holística para determinação de caudais ambientais em rios mediterrânicos, sustentado na vegetação ripária e espécies piscícolas. São descritas várias circunstâncias de modelação recorrendo ao modelo CASiMiR-vegetation com o propósito de suportar a investigação que visa aos objetivos da tese. Os principais resultados já alcançados nesta investigação são realçados para ilustrar os desenvolvimentos que podem ser alcançados a partir do uso de tal modelo.

**Palavras-chave**: Modelação de vegetação ripária, caudais ambientais, restauro fluvial.

## Abstract
The CASiMiR-vegetation model is a software that recreates the physical processes influencing the survival and recruitment of riparian vegetation, based on the relationship between ecologically relevant flow regime components and riparian vegetation metrics that reflect the vegetation's responses to flow regime change. Working at a flow response guild level, this tool outperforms equivalent models by overriding various restrictions of the conventional modeling approaches. The potential of the CASiMiR-vegetation model is revealed in its application to different case studies during the development of a holistic approach to determine environmental flows in lowland Mediterranean rivers, based on woody riparian vegetation and fish species. Various modeling circumstances are described where CASiMiR-vegetation model was used

with the purpose of sustaining the research addressing the thesis objectives. The main findings already accomplished in this research are highlighted to illustrate the outcomes that can be attained from the use of such a model.

**Keywords**: riparian vegetation modeling, environmental flows, river restoration.

## 1. INTRODUCTION

The river natural flow regime is the foundation of the ecological integrity of aquatic and riparian ecosystems (Poff *et al.* 1997). A modification in the river natural flow regime influences the geomorphology (Lloyd *et al.* 2004), ecology (Poff and Zimmerman 2010) and biology (Stromberg *et al.* 2010a) of these ecosystems producing dramatic effects on both aquatic and riparian species (Poff and Zimmerman 2010). Nonetheless, river regulation is a global phenomenon (Arthinghton *et al.* 2006) and is expected to further increase with climate change due to augmented water demand (Palmer *et al.* 2008). Accordingly, as societal demand for water increases we need guidelines for managing reservoir outflows and water abstractions (Poff *et al.* 1997; Hughes and Rood 2003).

Flow restoration became mandatory for European managers, as the Water-Framework Directive aims to achieve good ecological status in all water bodies, where the flow regime must be capable of sustaining biological elements and river processes (Acreman and Ferguson 2010). Currently, the assessment of environmental flows is in general based on minimum needs, implemented as a minimum constant flow of the river or as a percentage of the natural hydrological regime (Poff *et al.* 2010). Two dimensional (2D) habitat models became a powerful tool used to simulate hydraulic patterns and species habitat suitability (Santos and Ferreira 2008) making habitat simulation approaches the most scientific defensible methodology in ecological flow determination (Dunbar *et al.* 1998; Jowett *et al.* 2008) aiming at instream species requirements. However, in most cases only the instream requirements are considered and few species are usually used, mostly fish (Poff *et al.* 1997; Annear *et al.* 2002). Therefore, environmental flows are still biased towards this taxa (Tharme 2003; Gillespie *et al.* 2014) and carry on lacking the long-term perspective of the riverine ecosystem (Stromberg *et al.* 2010b). Different biological communities need to be considered in environmental flow definition along with its response to diverse water regime elements like magnitude, frequency, duration, timing and flashiness (Poff *et al.* 1997; Acreman and Ferguson 2010).

In this sense, the riparian ecosystem is one of which its flow requirements have been seldom investigated in environmental flow science. The riparian ecosystem ensures the connection between the aquatic and terrestrial ecosystems having an obvious influence in the improvement of the aquatic systems habitat (Naiman and Décamps 1997; Naiman *et al.* 2005) and biological conservation (Broadmeadow and Nisbet 2004; Van Looy *et al.* 2013). The riparian vegetation is especially vulnerable to flow regime changes (Perry *et al.* 2012) because its adaptations and life-histories are synchronized according to the variable conditions of the river dynamics (Stella *et al.* 2006). This 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). The flow regime is the most important driver and shaper of the riparian habitat (Toner and Keddy 1997; Karrenberg *et al.* 2002; Rood *et al.* 2003; Merritt *et al.* 2010), particularly the modification of flood cycles, changing the frequency, duration and magnitude of floods, which is the main factor influencing riparian vegetation patterns (Loučková 2012) and a well-balanced riparian vegetation dynamics (Tabacchi *et al.* 1998; Gergel *et al.* 2002; Rood *et al.* 2003).

Accordingly, researchers and water managers need to be capable of foreseeing the riparian habitat response to any flow regime in order to better understand the processes by which the riparian ecosystems evolve and are maintained (Lake *et al.* 2007). In this context, the dynamic vegetation models are particularly interesting due to their capacity to simulate the modification of vegetation features, such as stand age and the relative proportion of the succession phases (Merritt *et al.* 2010) accordingly to the ecologically relevant elements of flow regime, such as magnitude, frequency, rate of change, inter-annual variability and sequencing of flows (Rood *et al.* 2005). These tools can therefore provide researchers and water managers with the necessary long-term perception of the riparian ecosystem dynamics to evaluate conservation necessities which time scale is most of the times difficult to conceal with decision making deadlines (Stromberg *et al.* 2010a).

The riparian vegetation modeling presented in this work is mainly performed using CASiMiR-vegetation model (Benjankar *et al.* 2009). This tool recreates the physical processes influencing the survival and recruitment of riparian vegetation, resulting in a temporal and spatial illustration of the riparian vegetation patches. The dynamic vegetation model CASiMiR-vegetation has proved to be a valuable instrument to perform this task (see Benjankar 2009; Benjankar *et al.* 2009; Egger *et al.* 2009a; Egger *et al.* 2009b; Benjankar *et al.* 2011; García-Arias *et al.* 2011; Rivaes *et al.* 2011; Benjankar *et al.* 2012; Egger *et al.* 2012; Egger *et al.* 2013; García-Arias *et al.* 2013; Rivaes *et al.* 2013; Politti *et al.* 2014; Rivaes *et al.* 2014; Rivaes *et al.* 2015b). The tool is a dynamic rule-based spatially distributed model that simulates vegetation dynamics based on the relationship between ecologically relevant flow regime components (Poff *et al.* 1997) and riparian vegetation metrics that reflect the vegetation's responses to flow regime change, such as age distribution, composition and cover (Merritt *et al.* 2010). Furthermore, the physical processes are modeled by hydromorphological zones, each one with different calibration parameters. The major advantage of this model is that it works at a flow response guild level, where the succession phase is the modeling unit representing the structural diversity of the riparian ecosystem. This feature allows overriding various restrictions of the conventional modeling approaches, like the site or species specificity of many models, thus allowing for the simultaneous application of this tool in different case studies with comparable results.

This paper is intended to present the potential of the CASiMiR-vegetation model by revealing its application in different case studies during the development of a holistic approach to determine environmental flows in lowland Mediterranean rivers based on riparian vegetation and fish species. This approach aims to recreate the typical intra-annual hydrological variability, whilst incorporating the inter-annual flow variance by combining the use of primarily two predictive models: 1) a dynamic vegetation model using riparian patches 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) a hydrodynamic model to perform physical habitat simulations using target fish species to predict low flow needs, hence, the maintenance of shorter life cycles, including recruitment, feeding and sheltering. This holistic concept is approached by the Building Block Methodology (King and Louw 1998) but instead of being mostly based on multi-expert-judgment, it uses numerically robust techniques, which is an important aspect especially in European rivers where flow and biological information are becoming less empirical (Hughes and Rood 2003). So far, such an attempt encompassing biotic, hydrological and hydraulic features and different time scales has not occurred in Iberian rivers or probably 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.

The following sections describe various modeling circumstances where CASiMiR-vegetation model was used with the purpose of sustaining the research addressing relevant riverine ecology topics, such as the structural and functional changes of river communities affected by long-term flow changes, the flow requirements of riparian vegetation, or the ecological feedbacks of riparian vegetation on aquatic communities. In addition, the main findings already accomplished in this research are highlighted to illustrate the outcomes that can be attained from the use of such a model.

## 2. METHODS

### 2.1. Study site selection

In Portugal, the CASiMiR-vegetation model was already applied to five study sites, namely, ODLC, MTRC, OCBA, OCPR and AVTO. Currently, a sixth study site was by now surveyed (VNBQ) and data is being prepared to run the floodplain vegetation model (Figure 1). The considered case studies will be used according to its best suitability for the particular scientific question to be addressed in each of the following sections. All the case studies correspond to rivers with marked Mediterranean flow regime but with diverse hydrologic and geomorphologic characteristics, and with different river regulation circumstances (Table 1).

The Mediterranean flow regime that typifies all the study sites is characterized by a great intra-annual variability where in general a low flow exists mainly during the wet season, from October to March, interrupted by frequent flash floods as a result of heavy rain events. In contrast, during the rest of the year, river flow is very low or even null due to the characteristic rain shortage occurring during this season.

The riparian woodland is similar in all the study sites. Ashes (*Fraxinus angustifolia*) and willows (*Salix sp.*) are the predominant species but tamarisks (*Tamarix africana*), poplars (*Populus sp.*), alders (*Alnus glutinosa*) and the Iberian endemism Tamujo (*Flueggea tinctoria*) can also be found in those stretches according to their occurrence distribution and with more or less representativeness. Nevertheless, the ecological succession pathways of the riparian vegetation were found the same in all the study sites (Figure 2).

**Figure 1. Study sites location.** Dark grey areas with white outline are the watersheds of the main rivers (thick black lines) in which the study sites are placed, namely, ODLC in the Odelouca river, MTRC in the Sado river, VNBQ in the Tagus river, AVTO in the Alvito river, and OCBA and OCPR in the Ocreza river.

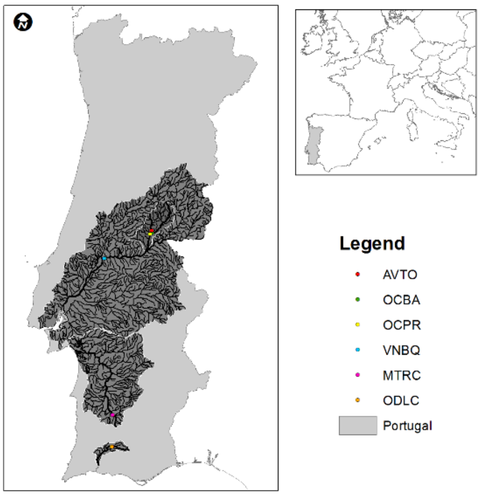
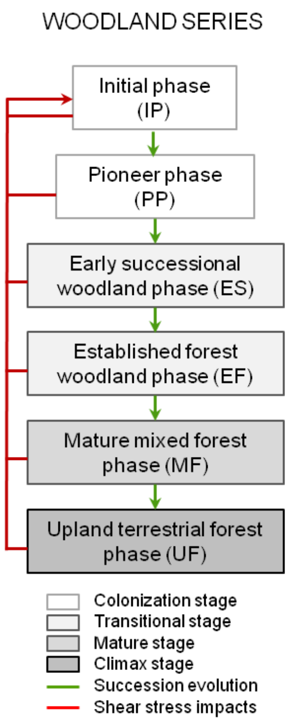


**Table 1. Study sites characterization.**

| | Study site | ODLC | MTRC | VNBQ | OCBA | OCPR | AVTO |
|---|---|---|---|---|---|---|---|
| Study site characteristics | River | Odelouca | Sado | Tagus | Ocreza | Ocreza | Alvito |
| | Location | 37º23'05,00''N; 8º18'39,46''W | 37º44'11,75''N; 8º18'04,23''W | 39º27'20,31''N; 8º24'45,73''W | 39º44'09.78''N; 7º44'24.75''W | 39º43'16.88''N; 7º46'01.05''W | 39º45'42.03''N; 7º45'03.62''W |
| | Stretch length (m) | 400 | 500 | 1800 | 500 | 300 | 300 |
| | Altitude (masl) | 132 | 93 | 21 | 140 | 117 | 163 |
| | Main substrate | Gravel | Sand and fine sediment | Sand and gravel | Boulders | Boulders | Boulders |
| | Mean annual discharge ($m^3/s$) | 2.5 | 0.01 | 336.0 | 8.7 | 12.2 | 2.5 |
| | Distance to source (km) | 35 | 24 | 883.5 | 62 | 67 | 30 |
| | Regulated | No | Yes | Yes | No | No | No |
| | Distance to upstream dams (km) | - | 1 | 42 and 18 | - | - | - |
| | Directly regulating dams | - | Monte da Rocha | Belver and Castelo de Bode | - | - | - |
| Watershed characteristics | Total watershed ($km^2$) | 186 | 252 | 67520 | 779 | 1037 | 177 |
| | Mean annual precipitation (mm) | 750 | 561 | 893 | 854 | 910 | 1102 |
| | Watershed regulated by dams (%) | 0 | 96 | 97 | 0 | 0 | 0 |

**Figure 2. Pathways of the riparian vegetation ecological succession occurring in the considered study sites.**




From: García-Arias *et al.* 2013.

### 2.2. Development and calibration of a dynamic riparian vegetation model

The authors have been working together in the development of the CASiMiR-vegetation model since 2009, essentially testing and improving the newer model versions (latest version available at http://www.casimir-software.de/ENG/download_eng.html). The CASiMiR-vegetation model was applied in five study sites, namely, ODLC, MTRC, OCBA, AVTO and OCPR. Calibration was performed by comparison of the model expected vegetation maps and the observed vegetation maps of the study sites. To model the expected riparian vegetation maps, CASiMiR-vegetation model ran a decade of the historical hydrological regime in each study site, matching the last modeling year with the year of the study site survey. By these means the model produced the expected riparian vegetation map that according to this tool was likely to exist in the very same year of the survey. Comparing both expected and observed vegetation maps makes it possible to assess the accuracy of the model and, therefore achieve calibration when improving model accuracy by model parameter tuning is no longer possible. Furthermore, the model was temporally and spatially validated. Temporal validation was performed in the ODLC study site using the historical hydrological information and an observed vegetation map obtained by remote sensing of the study site at a different previous year. The spatial validation of the model was executed in the OCPR study site, located 5 km downstream of the OCBA study site, with the calibration data determined for the latter case. Classification accuracy was evaluated using the quadratic weighted version of Cohen's Kappa (Cohen 1960).

### 2.3. Evaluate the influence of the main drivers of riparian vegetation's ecological succession in the determination of riparian vegetation flow regime requirements

The ecological succession of riparian vegetation is driven by large and small scale drivers that influence the riparian habitat at different levels (e.g. Scott *et al.* 2005; Whited *et al.* 2007). Large scale drivers influence riparian vegetation on a landscape dimension and are expected to influence the riparian patch mosaic by means of flow regime modification. Small scale drivers will likely have particular influence on a patch extension affecting mostly the local habitat conditions of the riparian vegetation.

The seasonality and variability of temperature and rainfall are accounted as major drivers of riparian vegetation's ecological succession. The influence of these large scale drivers were assessed through the analysis of climate change scenarios by comparison of the existing riparian landscapes governed by the actual rainfall patterns and the expected ones ruled by future climate change scenarios. The climate change scenarios were attained from the forecasts of global and regional circulation models applied to Portugal country limits (Santos *et al.* 2002; Santos and Miranda 2006). The CASiMiR-vegetation model was used to model the corresponding modified flow regimes in the ODLC study site and thus determine the expected riparian landscape changes occurring in the Mediterranean climate driven by different climate change scenarios (see Rivaes *et al.* 2013 for a better understanding).

### 2.4. Approach riparian vegetation restoration measures by flow regime management

The riparian vegetation restoration measures by flow regime management are interpreted in this work as the necessary flushing flows to be released by dams in order to minimize the effects of flow regulation on downstream riparian habitats. The assessment of the riparian vegetation disturbance requirements, i.e., the necessary floods to maintain the riparian patch mosaic as close as possible to the natural condition, was performed in ODLC, OCBA, AVTO and OCPR study sites. Riparian vegetation disturbance requirements were assessed by modeling riparian vegetation according to different flushing flow regimes in CASiMiR-vegetation model and determining the best flow regime capable of maintaining as most as possible the naturalness of the riparian patch mosaic. The resulting expected vegetation maps were analyzed using different map comparison methods. The inputted flow regimes considered a decade of floods combining two different recurrence intervals which generated a whole range of disturbance regimes composed by main floods interposed by intermediate floods (see Rivaes *et al.* 2015b for a better understanding).

### 2.5. Assess the ecological feedbacks of riparian vegetation management on aquatic communities

Using the knowledge generated in the previous sections, particularly the flow regime requirements of riparian communities, one evaluated the repercussions of such riparian vegetation management on the aquatic communities. This allows to understand how the management and consequently the improvement of the riparian habitat in regulated rivers influence the aquatic habitat. The CASiMiR-vegetation model was applied in OCBA study site to produce different scenarios of riparian landscapes derived from diverse flow regime management setups, later used as the matrix for the habitat characteristics inputted into the hydrodynamic modeling of fish species. Besides the natural flow regime, which was used as the natural riparian habitat benchmark, two flow regime management alternatives were selected, namely, an environmental flow regime regarding only fish requirements (hereafter named fish e-flow) and an environmental flow regime taking into account both fish and riparian requirements (hereafter named fish&flush e-flow). The expected riparian vegetation maps resulting of such flow regimes provided the channel roughness characterization of the riverbed according to the spatial extent of the succession phases existing in the study site. Different roughness was attributed to the succession phases based on literature roughness measurements on similar vegetation types. The provided habitat availability of aquatic species was determined using River2D model (Steffler *et al.* 2002) according to the riparian habitats produced by each management alternative (see Rivaes *et al.* 2015a for a better understanding).

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

Using the previous modeling approaches, flow requirements will be determined to maintain both natural riparian patchiness 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 built for a multiannual period, using the minimum requirements obtained for riparian vegetation and fish habitat. CASiMiR-vegetation model supports the establishment of the riparian vegetation requirements and the best flow regime addressing those requirements. A first approach was tested in OCBA and AVTO case studies. The riparian vegetation modeling followed the methodology presented in Rivaes *et al.* 2015b.

### 2.7. 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. Regarding riparian vegetation, the CASiMiR-vegetation model can be applied in regulated rivers to recreate natural floodplain conditions prior to river regulation to be used as the biological and physical reference conditions for ecological status assessment and restoration guidelines (Acreman and Ferguson 2010). Based on reference site information to carry out model parameterization regarding the natural condition of riparian vegetation, the CASiMiR-vegetation model can ran the hypothetical or historical natural flow regime and determine the expected riparian patch mosaic in natural unregulated circumstances. The CASiMiR-vegetation model was applied to the MTRC study site to recreate its expected natural floodplain to be used as benchmark to following studies (see Rivaes *et al.* 2015b for a better understanding).

## 3. RESULTS

### 3.1. Development and calibration of a dynamic riparian vegetation model

The CASiMiR-vegetation model was successfully calibrated for Mediterranean rivers achieving in all the study sites a quadratic weighted kappa ranging from 0.51 to 0.66 (Table 2). Such classifications on model accuracy range from moderate to good classification agreements (Landis and Koch 1977; Altman 1991; Viera and Garrett 2005). The model was temporally and spatially validated within the same classification agreement range but always with better results (Table 3).

**Table 2. CASiMiR-vegetation calibration results in the Portuguese study sites ODLC, MTRC, OCBA and AVTO.**

| Study site | Quadric weighted kappa |
|---|---|
| **ODLC** | 0.51 |
| **MTRC** | 0.60 |
| **OCBA** | 0.61 |
| **AVTO** | 0.66 |

**Table 3. CASiMiR-vegetation validation results in the Portuguese study sites ODLC and OCPR.**

| Study site | Validation | Quadric weighted kappa |
|---|---|---|
| **ODLC** | Temporal | 0.54 |
| **OCPR** | Spatial | 0.68 |

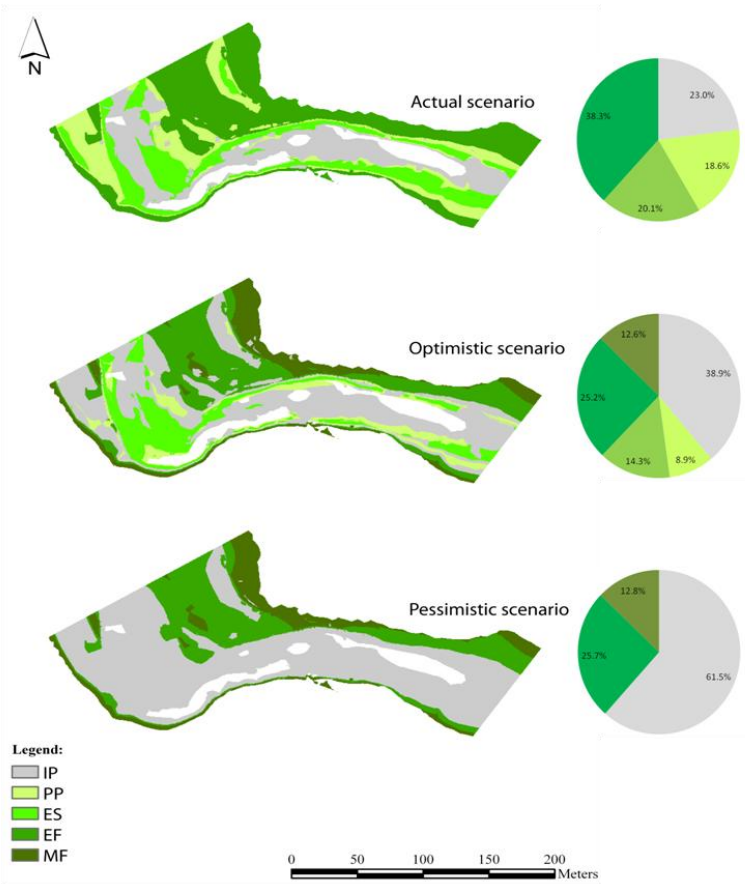
### 3.2. Evaluate the influence of the main drivers of riparian vegetation's ecological succession in the determination of riparian vegetation flow regime requirements

Climate change scenarios forecast a change in global temperature and rainfall patterns which in turn will affect river hydrological regime. The intensification of heavy rain events during winter along with longer and harsher droughts during summer will determine the increased retrogression of riparian vegetation near the river channel due to the enlarged morphodynamic disturbance of floods and the inability to reestablish in those areas again due to the reduced soil water moisture. These conditions 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 (Rivaes *et al.* 2013) (Figure 3). These results are particular of the Mediterranean climate, as in temperate rivers the climate change will not cause such drastic effects on riparian vegetation (Politti *et al.* 2014; Rivaes *et al.* 2014).

### 3.3. Approach riparian vegetation restoration measures by flow regime management

Different artificial flushing flow regimes can influence the riparian vegetation downstream of dams (Figure 4). These results and similar recently published ones (see Rivaes *et al.* 2015b) evidence that vegetation encroachment is mainly prevented by floods with a recurrence interval of at least 2 years, although environmental flow regime planning to comply with riparian vegetation requirements is watershed-specific. Notwithstanding, results in different river basins tend to analogous results where the artificial maintenance of the riparian habitat downstream of dams can be performed by reservoir flows in a flow regime fashion of a pluriannual time schedule considering floods with more than one recurrence interval (Figure 5). A detailed analysis of the kappa statistic shows collectively that the best disturbance regime is composed by 10-year floods interspersed by 2 or 3-year floods.

**Figure 3. Climate change effects on Mediterranean riparian ecosystems obtained by using the CASiMiR-vegetation model.** Riparian vegetation is detailed by succession phase, namely, Initial phase – IP, Pioneer phase – PP, Early succession phase – ES, Established forest phase – EF and Mature forest phase – MF.




(Adapted from: Rivaes *et al.* 2013).

**Figure 4. Expected riparian vegetation maps of the OCBA study site according to the different modeled flushing flow regimes**.

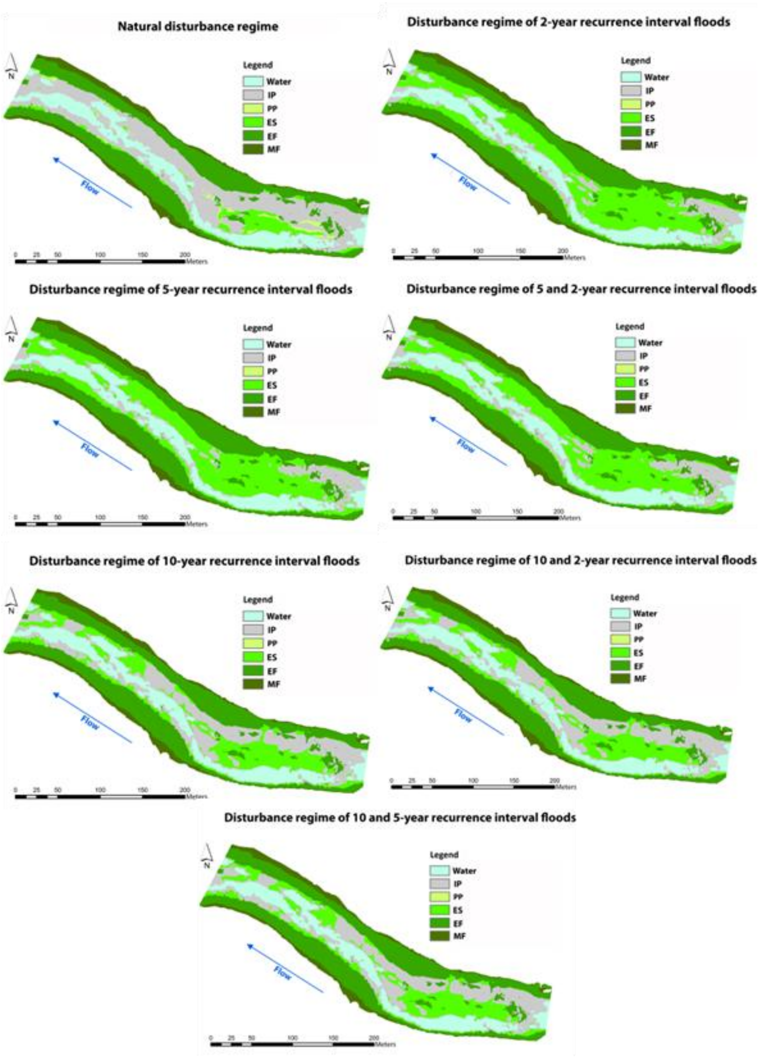
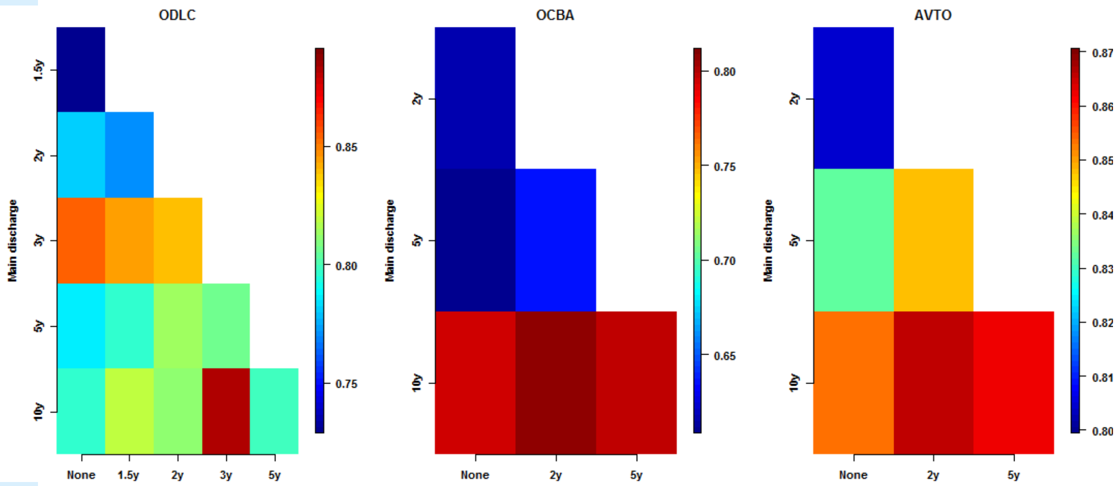



**Figure 5. Map agreement analysis of the expected vegetation maps according to each artificial flushing flow regime compared to its natural reference vegetation map in ODLC, OCBA and AVTO study sites.**



### 3.4. Assess the ecological feedbacks of riparian vegetation management on aquatic communities

The different flow regimes considered in the riparian vegetation modeling instigate distinct long-term structural adjustments of the riparian habitat resulting in singular riparian vegetation mosaics after a decade of exposition to each flow regime (Figure 6). Vegetation encroachment is evident in the fish e-flow scenario where there is a great reduction of the unvegetated riverbed area (in initial phase) substituted by more evolved succession phases. The fish&flush e-flow is capable of maintaining the proportion of the succession phases in a very similar state of the natural habitat. The fish e-flow regime creates in general weighted usable areas (WUA) much less related to the natural habitat than the fish&flush e-flow regime. In the majority of the cases the fish e-flow regime provides less WUA's but there are some months that for particular species this WUA is increased. Nevertheless, the species juveniles appear to be the most affected ones (Figure 7).

**Figure 6. Porportion of each succession phase area in the riparian patch mosaic instigated by the different considered flow regimes, namely, natural, fish e-flow and fish&flush e-flow.**

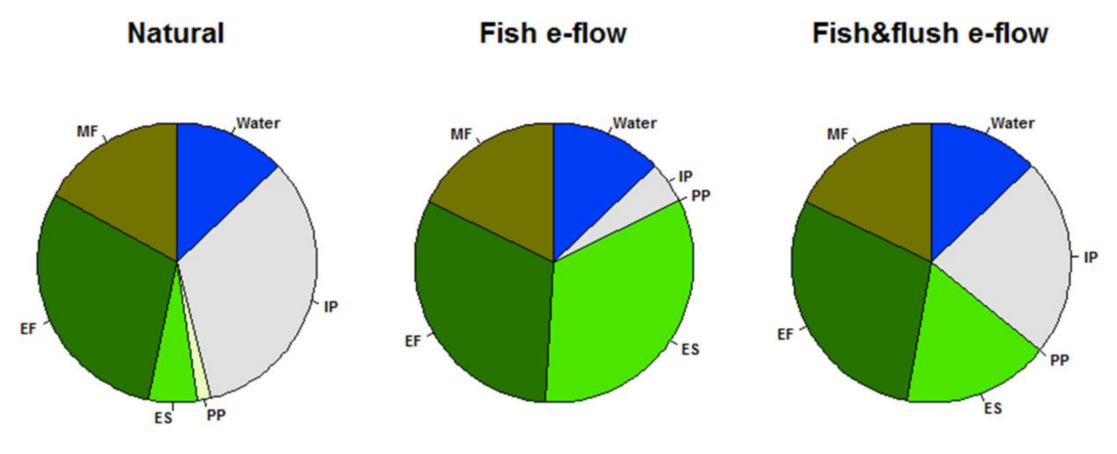
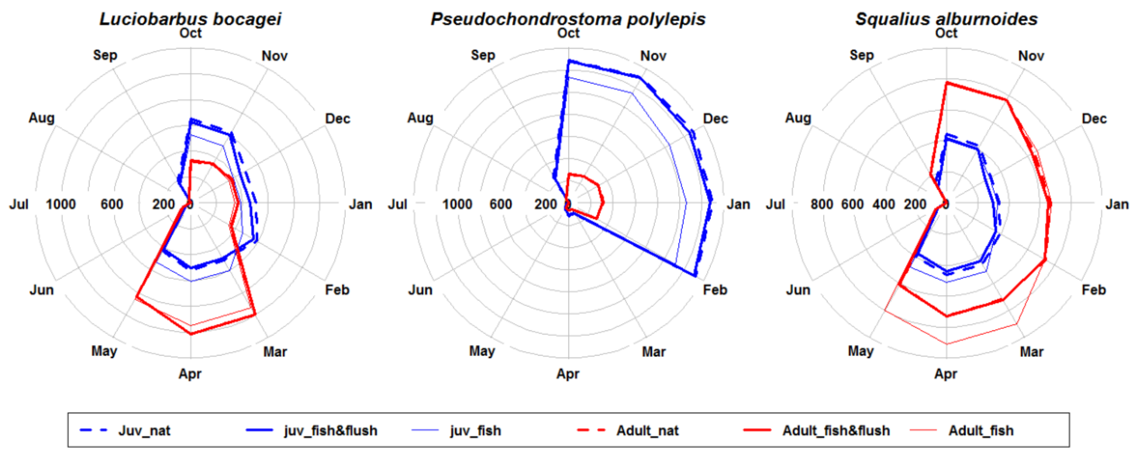



**Figure 7. Habitat weighted usable areas ($m^2$) of the considered species for the entire hydrologic year, provided by the habitats generated by the natural flow regime (thick dashed line), fish&flush e-flow regime (thick line) and fish e-flow regime (thin line).** Blue lines stand for species juveniles and red lines for adults.



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

A preliminary version of the holistic frame was successfully applied for the first time in OCBA and AVTO study sites. Considering the riparian and fish requirements determined previously, it was possible to build an environmental flow regime for each study site in a multiannual fashion that promotes the intra- and inter-annual flow variability of the different natural flow regime components. This environmental flow regime is composed of mean monthly discharges to meet fish habitat requirements and floods with different recurrence intervals to cope with the riparian vegetation requirements (Figure 8).

### 3.6. Setting reference conditions for environmental flows

The CASiMiR-vegetation model was applied to the MTRC study site in order to recreate its probable natural floodplain, based on the actual geomorphology and in the natural flow regime that would exist without flow regulation. In this hypothetical unregulated scenario, it is possible to perceive that the vegetation encroachment is not able to settle inside the river channel. This riparian vegetation map defines the riparian patch mosaic that would exist if the local flow regime was natural, representing therefore a benchmark for riparian vegetation patch mosaic in this study site (Figure 9).

**Figure 8. Environmental flow regime determined for the OCBA study site regarding riparian and fish requirements.** Blue line stands for the mean monthly discharge adressing fish requirements and green columns for the maximum discharge of the floods prescribed to address riparian vegetation requirements.

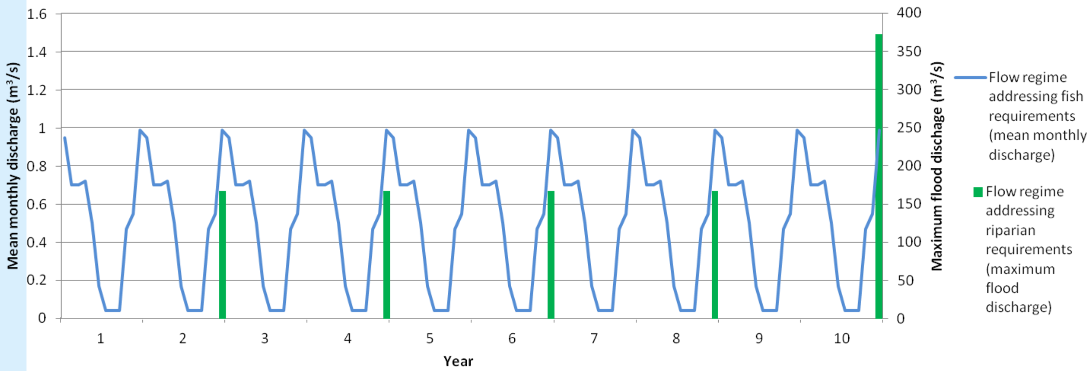
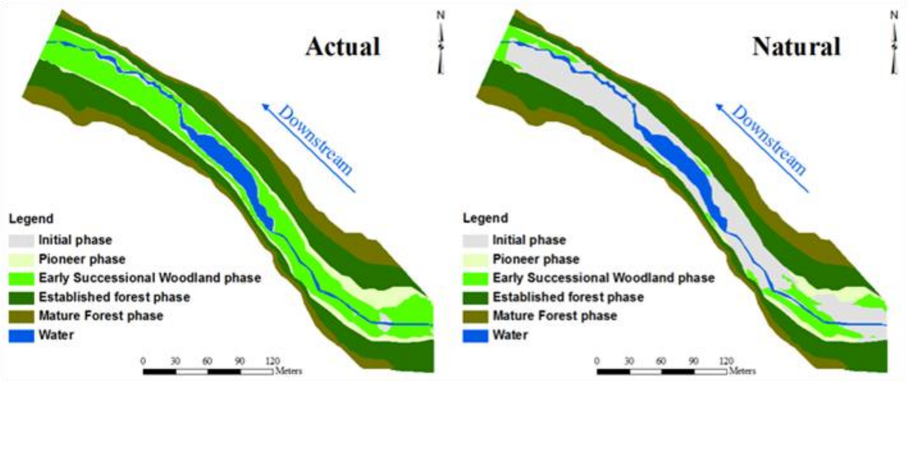



**Figure 9. Observed (Actual) and hipotethical natural (Natural) vegetation maps of the MTRC study site, created by the CASiMiR-vegetation model.**



## 4. DISCUSSION

This paper intended to disclose and broadcast the potential contribution that CASiMiR-vegetation model can provide to riparian vegetation and freshwater systems research. Throughout the different sections of this article one shows the support that this tool is rendering in particular to the development of a holistic approach for the determination of environmental flows in lowland Mediterranean rivers based on riparian vegetation and fish species.

The CASiMiR-vegetation model was applied to different case studies and flow regimes with the purpose of backing up environmental flow research, and the main findings already accomplished in this research were highlighted to illustrate the outcomes that can be attained from the use of such a model. The model was properly calibrated and validated in Mediterranean rivers with substantial accuracy. These results, together with similar ones achieved in study sites located all over the world (Egger *et al.* 2009b; Benjankar *et al.* 2011; Egger *et al.* 2012; García-Arias *et al.* 2013), show the robustness of the model and its capacity to correctly reproduce the riparian vegetation dynamics facing the main aspects of river disturbance in the more diverse cases.

After calibration, the CASiMiR-vegetation model was firstly applied in Portugal to understand the effects magnitude of a shift in the large scale drivers on riparian vegetation. Particularly, we assessed the influence of modified flow regimes originated by modified rainfall patterns driven by climate change. Climate change scenarios project for the year 2100 a change in the Mediterranean climate towards more intense winter floods, concentrated in a smaller period, while summer droughts will be more prolonged and harsh (Santos *et al.* 2002; Santos and Miranda 2006). Accordingly to CASiMiR-vegetation model, these conditions will determine the removal of the pioneer and young succession phases in the inner areas of the river and the aging of the remaining ones (Rivaes *et al.* 2013). Due to the advantage of the model working fashion (using flow response guilds), results were comparable to similar European studies, revealing the increased distress that Mediterranean riparian ecosystems will endure in the future when compared with temperate or mountain flow regimes (Politti *et al.* 2014; Rivaes *et al.* 2014).

Regarding the assessment of restoration measures by flow regime management, the modeling of the riparian vegetation according several different flow regimes revealed that the riparian requirements seem to be similar even between watersheds. All the natural case studies results were consistent in selecting the best disturbance regime composed by 10-year recurrence interval floods interspersed by 2 to 3-year recurrence interval floods. By these means, the metastable oscillation state (Formann *et al.* 2013) to which riparian vegetation is forced in natural systems can likely be preserved artificially in regulated rivers in order to maintain the viability and sustainability of the riparian communities. Accordingly, such flow regime must account for smaller floods to prevent vegetation encroachment as well as higher floods to rejuvenate the juvenile riparian patches. Additionally, these reservoir flows appear to be able to control vegetation encroachment without causing severe geomorphic impacts on downstream river channels and with minor water losses to dam managers (Rivaes *et al.* 2015b).

Managing the riparian ecosystem revealed also to bring advantages to the aquatic habitat. Our most recent study showed that improving the riparian habitat brings clear benefits to the aquatic habitat availability. Fish habitat availability changes accordingly to the long-term structural adjustments that riparian habitat endure following river regulation and therefore riparian vegetation requirements must be considered on environmental flows to assure the effectiveness of those in the long-term perspective of the fluvial ecosystem (Rivaes *et al.* 2015a).

The CASiMiR-vegetation model allowed to understand how the inter-annual variability of the flow regime must be maintained to prevent vegetation encroachment and promote the continuous rejuvenation of the young riparian patches. By these means it provided the necessary knowledge to build a preliminary version of the holistic approach which is the underlying purpose of this thesis. The CASiMiR-vegetation model also enabled the determination of the reference conditions in river systems where the ecological reference is unknown and unavailable. This feature is of great importance considering that knowing this benchmark is imperative to correctly determine the present quality of the ecosystems and appraise how they are evolving over time.

Notwithstanding, the developed approach 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).

In the end, this work shows that the CASiMiR-vegetation model can be applied to river systems with different hydrogeomorphologies and species diversity, providing correct and extremely useful information to support research in riparian and interrelated ecosystems.

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## References

ACREMAN, M. C., ALDRICK, J., BINNIE, C., BLACK, A., COWX, I., DAWSON, H., DUNBAR, M., EXTENCE, C., HANNAFORD, J., HARBY, A., HOLMES, N., JARRITT, N., OLD, G., PEIRSON, G., WEBB, J., WOOD P.. Environmental flows from dams: the water framework directive. **Proceedings of the Institution of Civil Engineers - Engineering Sustainability**, v. 162, n. 1, p. 13-22. 2009.

ACREMAN, M. C., FERGUSON, J. D.. Environmental flows and the European Water Framework Directive. **Freshwater Biology**, v. 55, p. 32-48, 2010.

ALTMAN, D. G. **Practical Statistics for Medical Research**. London,UK, Chapman & Hall, 1991. 613 p.

ANNEAR, T., CHISHOLM, I., BEECHER, H., LOCKE, A., AARRESTAD, P., COOMER, C., ESTES, C., HUNT, J., JACOBSON, R., JOBSIS, G., KAUFFMAN, J. B., MARSHALL, J., MAYES, K., SMITH, G., STALNAKER, C., WENTWORTH, R.. **Instream Flows for Riverine Resource Stewardship**, Instream Flow Council, 2002. 255 p.

ARTHINGTON, A. H., BUNN, S. E., POFF, L. N., NAIMAN, R. J. The challenge of providing environmental flow rules to sustain river ecosystems. **Ecological Applications**, v. 16, n. 4, p. 1311-1318. 2006.

BENJANKAR, R. **Quantification of reservoir operation-based losses to floodplain physical processes and impact on the floodplain vegetation at the Kootenai river, USA**. Doctor of Philosophy with a Major in Civil Engineering. Moscow, USA. University of Idaho (unpublished thesis), 2009. 288 p.

BENJANKAR, R., EGGER, G., JORDE, K. Development of a dynamic floodplain vegetation model for the Kootenai river, USA: concept and methodology. **7th ISE and 8th HIC**. 2009.

BENJANKAR, R., EGGER, G., JORDE, K., GOODWIN, P., GLENN, N. F. Dynamic floodplain vegetation model development for the Kootenai River, USA. **Journal of Environmental Management**, v. 92, n. 12, p. 3058-3070. 2011.

BENJANKAR, R., JORDE, K., YAGER, E. M., EGGER, G., GOODWIN, P., GLENN, N. F. The impact of river modification and dam operation on floodplain vegetation succession trends in the Kootenai River, USA. **Ecological Engineering**, v. 46, p. 88-97. 2012.

BORNETTE, G., AMOROS, C., PIEGAY, H., TACHET, J., HEIN, T. Ecological complexity of wetlands within a river landscape. **Biological Conservation**, v. 85, p. 35-45. 1998.

BROADMEADOW, S., NISBET, T. R. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. **Hydrology & Earth System Sciences**, v. 8, n. 3, p. 286-305. 2004.

COHEN, J. A coefficient of agreement for nominal scales. **Educational and Psychological Measurement**, v. 20, n. 1, p. 37-46. 1960.

DUNBAR, M. J., GUSTARD, A., ACREMAN, M. C., ELLIOT, C. R. N. **Overseas approaches to setting river flow objectives**. R&D Technical Report W145. Environment Agency, 1998. 78 p.

EGGER, G., EXNER, A., JENDEREDJIAN, A., JORDE, K., BENJANKAR, R.. Long term impacts of dam operation on riparian ecosystems - a dynamic floodplain vegetation model as an assessment tool. **HYDRO 2009, International conference and exhibition**, Lyon, France. 2009a.

EGGER, G., EXNER, A., JORDE, K., BENJANKAR, R. Impacts of reservoir operations on succession and habitat dynamics: calibration of a dynamic floodplain vegetation model for the kootenai river, USA. **7$^{th}$ ISE & 8$^{th}$ HIC**. Chile. 2009b

EGGER, G., POLITTI, E., GARÓFANO-GÓMEZ, V., BLAMAUER, B., FERREIRA, T., RIVAES, R., BENJANKAR, R., HABERSACK, H. Embodying interactions between riparian vegetation and fluvial hydraulic processes within a dynamic floodplain model: concepts and applications. In: I. MADDOCK, A. HARBY, P. KEMP AND P. WOOD (Ed.) **Ecohydraulics: an integrated approach**. Wiley Blackwell. 2013. p. 407-424.

EGGER, G., POLITTI, E., WOO, H., CHO, K., PARK, M., CHO, H., BENJANKAR, R., LEE, N., LEE, H. A dynamic vegetation model as a tool for ecological impact assessments of dam operation. **Journal of Hydro-environment Research**, v. 6, n. 2, p. 151-161. 2012.

FORMANN, E., EGGER, G., HAUER, C., HABERSACK, H.. Dynamic disturbance regime approach in river restoration: concept development and application. **Landscape and Ecological Engineering**, v. 10, n. 2, p. 1-15. 2013.

GARCÍA-ARIAS, A., FRANCÉS, F., ANDRÉS-DOMÉNECH, I., VALLÉS, F., GARÓFANO-GÓMEZ, V., MARTÍNEZ-CAPEL, F. Modeling the spatial distribution and temporal dynamics of Mediterranean riparian vegetation in a reach of the Mijares River (Spain). **EUROMECH Colloquium 523**, Clermont-Ferrand, France. 2011.

GARCÍA-ARIAS, A., FRANCÉS, F., FERREIRA, T., EGGER, G., MARTÍNEZ-CAPEL, F., GARÓFANO-GÓMEZ, V., ANDRÉS-DOMÉNECH, I., POLITTI, E., RIVAES, R., RODRÍGUEZ-GONZÁLEZ, P. M. Implementing a dynamic riparian vegetation model in three European river systems. **Ecohydrology**, v. 6, n. 4, p. 635-651. 2013.

GERGEL, S. E., DIXON, M. D. TURNER, M. G. Consequences of Human-Altered Floods: Levees, Floods, and Floodplain Forests along the Wisconsin River. **Ecological Applications**, v. 12, n. 6, p. 1755-1770. 2002.

GILLESPIE, B. R., DESMET, S., KAY, P., TILLOTSON, M. R., BROWN, L. E. A critical analysis of regulated river ecosystem responses to managed environmental flows from reservoirs. **Freshwater Biology**, v. 60, n. 2, p. 410-425. 2014.

HUGHES, F. M. R., ROOD, S. B. Allocation of River Flows for Restoration of Floodplain Forest Ecosystems: A Review of Approaches and Their Applicability in Europe. **Environmental Management**, v. 32, n. 1, p. 12-33. 2003.

JOWETT, I. G., HAYES, J. W., DUNCAN, M. J. **A guide to instream habitat survey methods and analysis**. N. S. a. Technology, 2008. 121p.

KARRENBERG, S., EDWARDS, P. J., KOLLMANN, J. The life history of Salicaceae living in the active zone of floodplains. **Freshwater Biology**, v. 47: n. 4, p. 733-748. 2002.

KING, J., LOUW, D. Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. **Aquatic Ecosystem Health and Management**, v. 1, n. 2, p. 109-124. 1998.

LAKE, P. S., BOND, N. REICH, P. Linking ecological theory with stream restoration. **Freswater Biology**, v. 52: n. 4, p. 597-615. 2007.

LANDIS, J. R. AND G. G. KOCH. The measurement of observer agreement for categorical data. **Biometrics**, v. 33, n. 1, p. 159-74. 1977.

LLOYD, N. J., QUINN, G., THOMS, M. C., ARTHINGTON, A. H., GAWNE, B., HUMPHRIES, P. WALKER, K. **Does flow modification cause geomorphological and ecological response in rivers? A literature review from an Australian perspective**. Technical report 1/2004. Canberra, Australia. CRC for Freshwater Ecology. 2004. 57 p.

LOUČKOVÁ, B. Vegetation-landform assemblages along selected rivers in the Czech Republic, a decade after a 500-year flood event. **River Research and Applications**, v. 28, n. 8, p. 1275-1288. 2012.

MERRITT, D. M., SCOTT, M. L., POFF, L. N., AUBLE, G. T., LYTLE, D. A. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. **Freshwater Biology**, v. 55, n. 1, p. 206-225. 2010.

NAIMAN, R. J., DÉCAMPS, H. The ecology of interfaces: Riparian zones. **Annual Review of Ecology and Systematics**, v. 28, p. 621-658. 1997.

NAIMAN, R. J., DÉCAMPS, H., MCCLAIN, M. E. (Eds.) **Riparia - Ecology, conservation and management of streamside communities.** London, UK, Elsevier academic press, 2005. 430 p.

PALMER, M. A., LIERMANN, C. A. R., NILSSON, C., FLÖRKE, M., ALCAMO, J., LAKE, P. S., BOND, N. Climate change and the world's river basins: anticipating management options. **Frontiers in Ecology and the Environment**, v. 6, n. 2, p. 81-89. 2008.

PERRY, L. G., ANDERSEN, D. C., REYNOLDS, L. V., NELSON, S. M. , SHAFROTH, P. B. Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America. **Global Change Biology**, v. 18, n. 3, p. 821-842. 2012.

POFF, L. N., ALLAN, J. D., BAIN, M. B., KARR, J. R., PRESTEGAARD, K. L., RICHTER, B. D., SPARKS, R. E., STROMBERG, J. C. The natural flow regime. **Bioscience**, v. 47, n. 11, p. 769-784. 1997.

POFF, L. N., RICHTER, B. D., ARTHINGHTON, A. H., BUNN, S. E., NAIMAN, R. J., KENDY, E., ACREMAN, M. C., APSE, C., BLEDSOE, B. P., FREEMAN, M. C., HENRIKSEN, J., JACOBSON, R., KENNEN, J. G., MERRITT, D. M., O'KEEFEE, J. H., OLDEN, J. D., ROGERS, K., THARME, R. E., WARNER, A. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. **Freshwater Biology**, v. 55, n. 1, p. 147-170. 2010.

POFF, L. N., ZIMMERMAN, J. K. H. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. **Freshwater Biology**, v. 55, n.1, p. 194-205. 2010.

POLITTI, E., EGGER, G., ANGERMANN, K., RIVAES, R., BLAMAUER, B., KLÖSCH, M., TRITTHART, M., HABERSACK, H. Evaluating climate change impacts on Alpine floodplain vegetation. **Hydrobiologia**, v. 737, n. 1, p. 225-243. 2014.

RIVAES, R., BOAVIDA, I., SANTOS, J., PINHEIRO, A. N. FERREIRA, M. T. The inbuilt long-term unfeasibility of environmental flows when disregarding riparian vegetation requirements. **Hydrol. Earth Syst. Sci. Discuss.**, v. 12, p. 10701–10737. 2015a.

RIVAES, R., RODRÍGUEZ-GONZÁLEZ, P. M., ALBUQUERQUE, A., FERREIRA, M. T. PINHEIRO, A. Uma nova ferramenta da restauro: aplicação de um modelo preditivo da evolução da vegetação ripícola em função das alterações hidrológicas. **Recursos Hídricos**, v. 32, n. 1, p. 29-41. 2011.

RIVAES, R., RODRÍGUEZ-GONZÁLEZ, P. M., ALBUQUERQUE, A., PINHEIRO, A. N., EGGER, G., FERREIRA, M. T. Riparian vegetation responses to altered flow regimes driven by climate change in Mediterranean rivers. **Ecohydrology**, v. 6, n. 3, p. 413-424. 2013.

RIVAES, R., RODRÍGUEZ-GONZÁLEZ, P. M., ALBUQUERQUE, A., PINHEIRO, A. N., EGGER, G., FERREIRA, M. T. Reducing river regulation effects on riparian vegetation using flushing flow regimes. **Ecological Engineering**, v. 81, p. 428-438. 2015b.

RIVAES, R. P., RODRÍGUEZ-GONZÁLEZ, P. M., FERREIRA, M. T., PINHEIRO, A. N., POLITTI, E., EGGER, G., GARCÍA-ARIAS, A., FRANCÉS, F. Modeling the Evolution of Riparian Woodlands Facing Climate Change in Three European Rivers with Contrasting Flow Regimes. **PLoS ONE**, v. 9, n. 10, p: e110200. 2014.

ROOD, S. B., BRAATNE, J. H., HUGHES, F. M. R. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. **Tree Physiology**, v. 23, n. 16, p. 1113-1124. 2003.

ROOD, S. B., SAMUELSON, G. M., BRAATNE, J. H., GOURLEY, C. R., HUGHES, F. M. R., MAHONEY, J. M. Managing river flows to restore floodplain forests. **Frontiers in Ecology and the Environment**, v. 3, n. 4, p. 193-201. 2005.

SANTOS, F. D., FORBES, K., MOITA, R. (Eds). **Climate Change in Portugal, Scenarios, Impacts and Adaptation Measures - SIAM project**. Lisbon, Portugal, Gradiva. 2002. 454 p.

SANTOS, F. D., MIRANDA, P. (Eds). **Alterações climáticas em Portugal cenários, impactos e medidas de adaptação, Projecto SIAM II**. Lisbon, Portugal, Gradiva. 2006. 506 p.

SANTOS, J. M., FERREIRA, M. T. Microhabitat use by endangered Iberian cyprinids nase

Iberochondrostoma almacai and chub Squalius aradensis. **Aquatic Sciences - Research Across Boundaries**, v. 70, n. 3, p. 272-281. 2008.

SCOTT, M. L., REYNOLDS, E. W., BRASHER, A. M. D., CAIRES, A. MILLER, M. E. **The structure and functioning of riparian and aquatic ecosystems of the Colorado Plateau - conceptual models to inform monitoring**. Southern Colorado Plateau Network. 2005. 107 p.

STEFFLER, P., GHANEM, A., BLACKBURN AND, J., YANG, Z. **River2D**. Alberta, CANADA. University of Alberta. 2002.

STELLA, J. C., BATTLES, J. J., ORR, B. K., MCBRIDE, J. R. Synchrony of seed dispersal, hydrology and local climate in a semi-arid river reach in California. **Ecosystems**, v. 9, n. 7, p. 1200-1214. 2006.

STROMBERG, J. C., LITE, S. J., DIXON, M. D. Effects of stream flow patterns on riparian vegetation of a semiarid river: implications for a changing climate. **River Research and Applications**, v. 26, n. 6, p. 712-729. 2010a.

STROMBERG, J. C., TLUCZEK, M. G. F., HAZELTON, A. F. AJAMI, H. A century of riparian forest expansion following extreme disturbance: Spatio-temporal change in Populus/Salix/Tamarix forests along the Upper San Pedro River, Arizona, USA. **Forest Ecology and Management**, v. 259, n. 6, p. 1181-1198. 2010b.

TABACCHI, E., CORRELL, D. L., HAUER, R., PINAY, G., PLANTY-TABACCHI, A.-M., WISSMAR, R. C. Development, maintenance and role of riparian vegetation in the river landscape. **Freshwater Biology**, v. 40, n. 3, p. 497-516. 1998.

THARME, R. E. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. **River Research and Applications**, v. 19, n. 5-6, p. 397-441. 2003.

TONER, M., KEDDY, P. A. River hydrology and riparian wetlands: a predictive model for ecological assembly. **Ecological Applications**, v. 7, n. 1, p. 236-246. 1997.

VAN LOOY, K., TORMOS, T., FERRÉOL, M., VILLENEUVE, B., VALETTE, L., CHANDESRIS, A., BOUGON, N., ORAISON, F., SOUCHON, Y. Benefits of riparian forest for the aquatic ecosystem assessed at a large geographic scale. **Knowl. Managt. Aquatic Ecosyst.**, v. 408, n. 6. 2013.

VIERA, A. J., GARRETT, J. M. Understanding interobserver agreement: the Kappa statistic. **Family Medicine**, v. 37, n. 5, p. 360-363. 2005.

WHITED, D. C., LORANG, M. S., HARNER, M. J., HAUER, F. R., KIMBALL, J. S., STANFORD, J. A. Climate, hydrologic disturbance, and succession: drivers of floodplain pattern. **Ecology**, v. 88, n. 4, p. 940-953. 2007.