Understanding multiple stressors in a Mediterranean basin: Combined effects of land use, water scarcity and nutrient enrichment

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HIGHLIGHTS
• The interplay of water scarcity and nutrients in river biotic state is addressed.
• Stressors were simulated through process-based modelling.
• Stressors, land use and environmental background were used to model biotic state.
• Agriculture and nutrient enrichment showed major effects on biotic state.
• Interactions should be carefully examined to avoid wrong conclusions for management.

ABSTRACT
River basins are extremely complex hierarchical and directional systems that are affected by a multitude of interacting stressors. This complexity hampers effective management and conservation planning to be effectively implemented, especially under climate change. The objective of this work is to provide a wide scale approach to basin management by interpreting the effect of isolated and interacting factors in several biotic elements (fish, macroinvertebrates, phytobenthos and macrophytes). For that, a case study in the Sorraia basin (Central Portugal), a Mediterranean system mainly facing water scarcity and diffuse pollution problems, was chosen. To develop the proposed framework, a combination of process-based modelling to simulate hydrological and nutrient enrichment stressors and empirical modelling to relate these stressors - along with land use and natural background - with biotic indicators, was applied. Biotic indicators based on ecological quality ratios from WFD biomonitoring data were used as response variables. Temperature, river slope, % of agriculture in the upstream catchment and total N were the variables more frequently ranked as the most relevant. Both the two significant interactions found between single hydrological and nutrient enrichment stressors indicated antagonistic effects. This study demonstrates the potentialities of coupling process-based modelling with empirical modelling within a single framework, allowing relationships among different ecosystem states to be hierarchized, interpreted and predicted at multiple spatial and temporal scales. It also demonstrates how isolated and interacting stressors can have a different impact on biotic quality. When performing conservation or management plans, the stressor hierarchy should be considered as a way of prioritizing actions in a cost-effective perspective.

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1. Introduction

Riverine environments have been increasingly imperilled by human activities and have become one of the most degraded systems in the world (Sala et al., 2000; Gleick, 2003). Degradation of rivers is caused by a multitude of individual stressors, originating from drivers such as agriculture, urbanization and climate change, which affect ecological patterns and processes through a highly and increasingly intricate cause-effect chain (Hering et al., 2015; Gieswein et al., 2017). The implementation of effective river management actions and appropriate ecological restoration actions greatly relies on the ability of researchers to disentangle this complex cause-effect chain into simple models that are capable of providing guidance for managers (Hering et al., 2015). For example, modelling frameworks that project multiple stressor effects on biological components of ecosystems under scenarios of changes in drivers and measures may provide especially useful tools to support decision making. Although there are several examples of such attempts (e.g. Fernandes et al., 2016; Segurado et al., 2016), these are still major challenges that river ecologists and managers are currently facing.

Rivers, because of their particular nature, pose additional challenges to assess and model the effects of multiple stressors. Multiple stressor combinations vary deeply along river longitudinal gradients and among different ecoregions (Schinegger et al., 2012), causing difficulties in disentangling their effects on biotic components from natural causes because of the co-variability of environmental conditions (Alahuhta and Aroviita, 2016). Moreover, very often the effect of single stressors may depend on the environmental and biotic settings where they are acting. Several studies show biotic alterations associated with human-induced disturbances (Branco et al., 2013) that have a strong regional pattern in terms of the degree of impact imposed on streams. Another challenge posed by rivers comes from their particular network structure. Rivers have a directional imposed by flow but they are more than “ribbons of aquatic habitat” (Fausch et al., 2002) because they form hierarchical dendritic network structures (Cote et al., 2010). These hierarchical, dendritic, directional networks are heterogeneous and continuous, with longitudinal, lateral, vertical, temporal (Ward, 1989) gradients that change at different scales (Frissell et al., 1986) and regions (Hering et al., 2015). This complexity severely hampers the ability to implement effective management actions in a river basin, especially if the goal is to achieve holistic targets e.g., taking into account all biotic quality elements and not do an over-“ribbon-like”-simplification.

The Water Framework Directive (WFD - European Commission, 2000) enforced the use of several biotic elements as indicators of surface water quality as an alternative to just water quality (Moss, 2007). The WFD involves defining biotic indicators of specific stresses, and their aggregation in the so-called one-out-all-out principle, but does not necessarily reflect a reliable indication of multiple stressors that recognize an integrated assessment of ecosystem health and mal-functioning (Hering et al., 2010). Additionally, most studies analyse solely the effect of individual stressors – a change in the environment that forces a response by the biological group of interest (Underwood, 1989) – on biotic indicators (Birk et al., 2012), notwithstanding the fact that often the response of an indicator to an isolated stressor is “wedge-shaped” – a clue that there are additional pressures at work that are expressed when the intensity of the isolated studied stressor is relatively low (Thomson et al., 1996; Friberg, 2010). It seems thus apparent that stressors interact, and, by doing so, create complex non-linear impacts. River systems are chiefly altered by hydromorphological degradation and diffuse pollution (EEA, 2012), which are themselves composed of several individual components. River regulation is widespread and severely alters flow velocity and water depth, creates vertical outflow drops that modify thermal and hydrology regimes of river systems and promotes the loss of original habitat which reduces heterogeneity and hampers the movement of river species (Segurado et al., 2013; Branco et al., 2014). Additionally, water quality is increasingly being deteriorated through urban, industrial and agricultural waste water. The combined impact of all these alterations has changed dramatically the constitution of river biotic communities (Allan, 2004).

Nowadays, increased water demand and climate change are likely to increase the magnitude and number of stressors acting upon river ecosystems and increase possible interactions. The interaction of different stressors can be manifold: additive when the response is predicted by the sum of the responses to isolated stresses; synergistic when the combined effect is greater than the sum of the effects of isolated stresses; or even antagonistic by creating responses smaller than those predicted (Underwood, 1989, but see Piggott et al., 2015 for an extensive review of the concepts). Deviations from additive effects among stressors tend to dominate, as shown by several studies (Côté et al., 2016; Nöges et al., 2016; Schinegger et al., 2016; Teichert et al., 2016; but see Gieswein et al., 2017 for opposing conclusions). Although studies focused on multiple stressors in aquatic environments are increasingly found in the literature (e.g. Ormerod et al., 2010; Côté et al., 2016; Feld et al., 2016; Jackson et al., 2016; Leal et al., 2016; Schinegger et al., 2016; Teichert et al., 2016), there is still a generalized lack of mechanistic understanding of stressors’ interactive effects, which is a barrier for the prediction of responses to changing environments, risk assessment, management, impact mitigation and restoration of ecosystems (Vinebrooke et al., 2004). The use of models facilitates the prediction of management and conservation actions and by doing so facilitates cost-effective measures to be selected for future application. But, models are just a simplification of reality. This is more evident for models applied to river networks given their intrinsic complexity. Although there are large numbers of unforeseeable eventualities, the use of models in river systems is accepted as a standard practice with relevant knowledge arising from them (Feld et al., 2016).

The main goal of this work is to understand the interplay between the effects of multiple stressors, land use, reach scale attributes and climate on several biotic quality indicators in the Sorraia Basin, a typical Mediterranean basin located in SW Portugal. The Sorraia River is mainly affected by water scarcity - both as a consequence of its Mediterranean nature and an extensive water abstraction for irrigation - and nutrient enrichment from diffuse pollution from agriculture. This case study is part of one of the modelling framework approaches developed within the MARS project (Managing Aquatic Ecosystems and Water Resources Under Multiple Stress; Hering et al., 2015; Feld et al., 2016) that aims to predict effects of multiple stressors at the basin scale under different future climate change models, storylines and management scenarios. For this purpose, a process-based approach is used to estimate several stressors and gradients at play in this basin, identiﬁes the stressor hierarchy and tests interactions among stressors in their effects on the biotic indicators. By doing so, this work, besides highlighting some specificities of working under a multi-stressor framework towards managing entire river basins that will predictably be affected by future alterations, advances knowledge and provides a theoretical basis that will facilitate management and conservation planning.

2. Materials and methods

2.1. Study area

The case study focused on the Sorraia Basin (Fig. 1), which has an area of 7730 km² and a length of 155 km. It flows towards the Tagus River estuary (outlet - latitude 38.83 and longitude — 8.99) and is the Tagus tributary with the largest basin area.

The Sorraia Basin is characterized by a Mediterranean climate with an average annual air temperature of 15.2 °C that ranges from 21.6 °C
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