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Assessing anthropogenic impacts on riverine ecosystems using nested partial least squares regression

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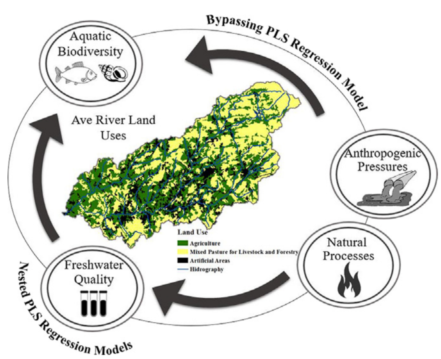
HIGHLIGHTS

- PLS regression and GIS were used to correlate spatial patterns of environmental descriptors in the Ave River basin (Portugal)
- Results linked ecological integrity declines observed downstream to poor treatment of domestic sewage
- The impact of industrial effluents and diffuse pollution sources are viewed as subsidiary
- Local factors have a greater influence on the values of BOD_5, COD, PO_4, NO_3 and Fe, than larger scale factors
- Mitigation of urban pollution relies on the improvement of wastewater treatment and not on the construction of new plants

GRAPHICAL ABSTRACT



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ABSTRACT

The results of three Partial Least Squares (PLS) regression models were used to gain a holistic view on the consequences of natural processes and anthropogenic pressures for water quality degradation and biodiversity decline in a multi-use watershed. The processes were soil erosion and wildfire risk; the pressures comprised land use conflicts, leachates from domestic and industrial waste, arable farming intensity and livestock density. Water quality was characterized for concentrations of nutrients (nitrate, phosphate), oxygen demands (Biochemical Oxygen Demand – BOD_5, Chemical Oxygen Demand – COD) and various metals (e.g., As, Cr). Ecological integrity was assessed by the recently developed MELI (Multiple Ecological Level Index). In total, 18 variables were processed in the regression models. Two models were called “nested models” because they dealt with initial (pressures), intermediate (water quality) and final (MELI) environmental descriptors, used as dependent (MELI, quality) or independent (quality, pressures) variables. The third was called “bypass model” because it dealt solely with initial and final descriptors. Overall, the results of PLS regression linked the ineffective treatment of domestic sewage to water quality and ecological integrity declines in the studied watershed. Put another way, all models recurrently affirmed the major role of local factors, meaning of point source pollution, in determining the quality of stream water and the integrity of freshwater ecosystems. Sources of diffuse pollution were accounted for as contributing factors in the PLS regressions, but their influence was scarcely perceptible in the results. The poor treatment of domestic effluents is a public concern. In their strategic plans for mitigating this problem in the

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forthcoming years, administrative authorities are concentrated on management initiatives to improve the quality of provided services, instead of considering the construction of new wastewater treatment plants.

1. Introduction

Rivers and associated watersheds are complex environments where humans and nature interact and interfere. Interference grew along with societal development and demographic expansion, being expressed in numerous and diverse pressures namely those exerted on stream hydro-morphology, freshwater quality and ecological integrity. In a variety of studies conducted across the globe, anthropogenic pressures and related environmental impacts were investigated and published. For example, papers like those by Beguería et al. (2006) or Hooke (2006) linked morphological alterations in river channels to human pressures, including the cultivation of steep slopes, frequent fires, deforestation and overgrazing, while García-Ruiz (2010) reviewed the effects of various land uses and their changes on soil erosion in Spain. In a couple of studies carried out in northern Portugal, Pacheco et al. (2014) as well as Valle Junior et al. (2014a) alerted for amplified soil losses where actual land uses deviate from natural uses set up by the soil's capability, being in a state of environmental land use conflict. The degradation of freshwater quality caused or influenced by anthropogenic activity was also documented in many publications. In some cases the papers were focused on monitoring programs (Chapman et al., 2016) in other cases on modeling exercises at stream, basin or multiple scales (Pacheco et al., 2015; Santos et al., 2015a; Schiller et al., 2008;Taylor et al., 2016). In general, the reported causes or sources of freshwater quality degradation consisted of crop irrigation (Chen et al., 2010), recurrent wildfires (Santos et al., 2015b), extreme weather events (Bertone et al., 2016; Mosley, 2015), environmental land use conflicts (Pacheco and Sanches Fernandes, 2016; Valle Junior et al., 2014b), urban or industrial effluents (Nyamangara et al., 2008) or multiple circumstances (Carey et al., 2013; Collin and Melloul, 2001; Garnier et al., 2013). In watersheds, the course of nutrients, metals and other dissolved constituents imported from the source areas may not stop in the aquatic media but continue to end up in the aquatic biota. To investigate consequences of degraded water quality for fish and macroinvertebrate communities in riverine ecosystems, a number of studies related the ecologic status of stream reaches with the physic-chemical parameters of stream water (Cortes et al., 2016; Valle Junior et al., 2015), namely linking the exposure to metals with the composition and structure of benthic macroinvertebrate communities (Piló et al., 2015) or with fish gill histopathological changes (Fonseca et al., 2016). Although the disturbance of riverine ecosystems and their services is directly caused by contamination of surface water and eutrophication derived therefrom, the original causes are human activities developed in rural and urban areas distributed all over the watershed. Local, smaller-scale abiotic and biotic features are nested within, and therefore constrained and controlled by successively larger-scale factors that act as environmental filters (Frissell et al., 1986; Poff, 1997; Hughes et al., 2008). This concept integrates the idea of a spatial filtering process along a hierarchy of spatial scales, shaping the communities at a given site, creating a distinct subset from the pool of potential colonizers since the existing assemblages are a result of the successive system of environmental filters, which are also mediated by the human intervention acting at each scale (Heino et al., 2002; Boyero, 2003; Bonada et al., 2005). For that reason, some studies established a direct relationships between anthropogenic pressures at various spatial scales and ecologic indicators (Cortes et al., 2011; Fonseca et al., 2013; Ives and Carpenter, 2007; Martinho et al., 2015; Oliveira et al., 2016; Santos et al., 2015c; Vaughan and Ormerod, 2010).

Despite the large number of scientific papers addressing specific issues on the relation between anthropogenic pressures, freshwater quality and ecological integrity, modeling exercises or review articles focused on the integration of all these topics are not abundant (Cooper et al., 2013; Cortes et al., 2013; Friberg, 2010; Paul and Meyer, 2008; Strayer et al., 2003). The general purpose of this paper is therefore to present a broadband view over a watershed, whereby the complex interplay among natural processes (erosion, wildfires), anthropogenic pressures (agriculture, livestock production, urban/industrial effluents), freshwater quality (macro nutrients, heavy metals) and ecological integrity can be better understood. The specific goal is to correlate ecological integrity with the most relevant threats. To accomplish the general and specific goals, a conceptual model was prepared where processes, pressures, quality parameters and ecological indicators are considered environmental descriptors along a hierarchy of interactions. The conceptual model was tested in the context of a heavily modified river basin (the Ave River basin, located in Portugal), using a number of parameters to describe the environmental descriptors. In a first stage, a number of sub-watersheds were characterized for these parameters and in a second step the resulting dataset was processed in Partial Least Squares (PLS) regression models. To fully accommodate the hierarchy of interactions, three model pathways were run, called nested or bypass sub-models. These encompassed quality versus integrity, processes/pressures versus integrity and processes/pressures versus quality regressions. The first two runs aimed to disclosure significant sensibility of ecological indicators to specific natural processes, anthropogenic pressures and freshwater quality parameters, while the third run aimed to connect the two previous models and hence the environmental descriptors. This study is novel because it looks to a watershed from a holistic point of view instead of being focused on specific parameters, like domestic sewage BOD_5, metal concentrations or macroinvertebrate diversity, which are one among many other variables. This is why we used regression models based on a large number of dependent and independent variables, instead of going through a descriptive statistics procedure on a parameter by parameter basis. Most parameters can theoretically be associated to multiple sources and amplified/attenuated by various processes. In a multiple – pressure basin, like the Ave, there is no easy way to ascribe the spatial pattern of a given parameter to a certain source or process. Only multiple layered models like nested PLS regression models can accomplish this task, the reason why one has adopted this approach in this study. By using this approach, one may eventually lose specific "alerts" from specific parameters but gain a broad view over the studied catchment. That was the objective and was accomplished.

2. Study area

The Ave River catchment is located in northern Portugal (Fig. 1). This catchment occupies an area of approximately 1322 km^2, being limited to the north by the Cávado basin, to the east by the Douro basin, to the south by the Leça basin and to the west by the Atlantic Ocean. The most important tributaries are the Este and Vizela streams. Altitudes in the watershed range from 0 m along the Atlantic coast to 1254 m at the catchment headwaters. The precipitation regime is characterized by prolonged dry periods followed by intensive rainstorms. The long-term annual rainfall (period: 1959/60–1990/91) varies from 1200 to 2000 mm, increasing towards the higher altitudes. Average temperatures range between 12.1 and 15 °C. The general information and average climatic data were compiled from https://www.ipma.pt. The Ave River basin is mostly shaped on Hercynian granites and Paleozoic