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Direct and indirect effects of multiple stressors on stream invertebrates across watershed, reach and site scales: A structural equation modelling better informing on hydromorphological impacts

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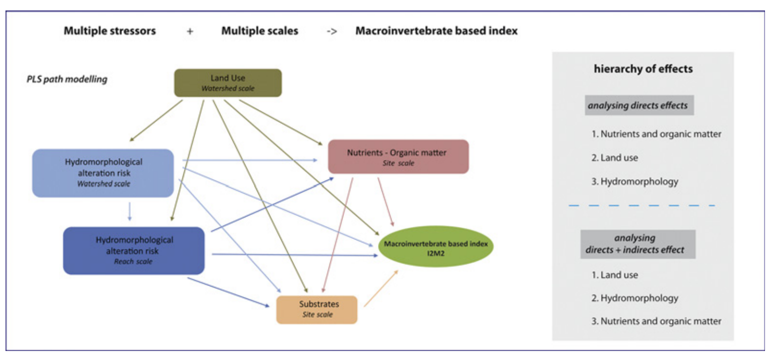
HIGHLIGHTS

- Land use has an effect on both hydromorphology and physico-chemistry and consequently has an indirect effect on biological condition of streams.
- Hydromorphology has a major indirect effect on macroinvertebrates.
- Site scale is important for explaining the biological condition of streams.

GRAPHICAL ABSTRACT



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ABSTRACT

The purpose of our approach was to take into account the nested spatial scales driving stream functioning in the description of pressures/ecological status links by analysing the results of a hierarchical model. The development of this model has allowed us to answer the following questions: Does the consideration of the indirect links between anthropogenic pressures and stream ecological status modify the hierarchy of pressure types impacting benthic invertebrates? Do the different nested scales play different roles in the anthropogenic pressures/ecological status relationship? Does this model lead to better understanding of the specific role of hydromorphology in the evaluation of stream ecological status?

To achieve that goal, we used the Partial Least Square (PLS) path modelling method to develop a structural model linking variables describing (i) land use and hydromorphological alterations at the watershed scale, (ii) hydromorphological alterations at the reach scale, (iii) nutrients-organic matter contamination levels at the site scale, and (iv) substrate characteristics at the sampling site scale, to explain variation in values of a macroinvertebrate-based multimetric index: the French I_2M_2.

We have highlighted the importance of land use effects exerted on both hydromorphological and chemical characteristics of streams observed at finer scales and their subsequent indirect impact on stream ecological status. Hydromorphological alterations have an effect on the substrate mosaic structure and on the concentrations of nutrients and organic matter at site scale. This result implies that stream hydromorphology can have a major indirect effect on macroinvertebrate assemblages and that the hierarchy of impacts of anthropogenic pressures on stream ecological status generally described in the literature - often determining strategic restoration priorities -

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has to be re-examined. Finally, the effects of nutrients and organic matter on macroinvertebrate assemblages are lower than expected when all the indirect effects of land use and hydromorphological alterations are taken into account.

1. Introduction

Streams are open systems, and the structure, composition and functioning of the biocenoses they host are closely linked to peri-riverine human activities. In any ecosystems, functional processes interact at multiple spatial and temporal scales (Hynes, 1975; Lévêque, 2001). Streams more or less directly collect the rainfall water within the watershed. Any alteration of the neighbouring terrestrial ecosystems has potential impacts on stream water flow and fluxes of elements - and thus on the downstream aquatic ecosystems - over long distance and at long-term. The linear structure of streams makes autochthonous biotic communities particularly vulnerable to both (i) transversal structures that disrupt water, sediment and biological flows; and (ii) engineered in-stream or riverine structures brought to protect neighbouring areas from extreme meteorological events (Wasson et al., 1993). It has long been recognized that (i) stream functioning is organized according to a hierarchy of spatial scales (Allan, 2004; Frissell et al., 1986; Poff et al., 1997; Roth et al., 1996; Thorp, 2014; Thorp et al., 2006) from the regional scale to the microhabitat scale via the watershed and reach scales, and that (ii) the processes and structures observed at the largest scales (regional, watershed) influence the processes and structures observed at the smallest ones (reach, site). Streams are therefore complex dynamic systems, resulting from continuous adaptations of the liquid and solid compartments in permanent interaction. The geological and geographic contexts coupled with the climatic and hydrological regimes govern stream hydromorphological characteristics (Omernik, 1987). The hydromorphological, hydraulic and thermal characteristics of streams drive the available within-stream physical habitats. Local physical habitats, chemical conditions and the composition and attributes of the potential pool of colonists will determine the local species assemblage, in terms of both composition and structure. In addition to this schematic view, account must be taken of the natural variability of habitats (e.g. inter-annual variations in thermal and hydrological regimes) to which biological communities should be adapted (Piffady et al., 2013).

Moreover, according to the DPSIR concept (Driving forces, Pressures, State, Impact and Response; Kristensen, 2004), human activities (agriculture, urbanization) create driving forces for changes in the abiotic components (physico-chemistry, hydromorphology) of streams via the effects of combined pressures (chemical discharges, physical alterations). These anthropogenic pressures can be ranked hierarchically according to the relative importance of their impact at the different nested spatial scales described by Frissell et al. (1986; from watershed to habitat). Large sectors of intense human activity (e.g. agriculture, urbanization, industries) can have severe impact on the physico-chemical, hydromorphological and hydrological characteristics of streams, via sediment transport alteration, nutrient enrichment, toxic pollution, hydrological modifications, riparian clearing or habitat loss (Allan, 2004; Novotny et al., 2009; Paul and Meyer, 2001). Moreover, flow management for flood prevention, hydroelectricity production and irrigation modify hydraulic regimes, with possible hydromorphological (e.g. disruption in sediment transport continuity, stream bed incision) and thermal (water warming) drawbacks that modify local habitat conditions for biotic communities (Poff et al., 1997; Verdonschot et al., 2016; Villeneuve et al., 2015). The local degradation of stream channel geometry can modify habitats and biogeochemical processes (e.g. disruption of lateral connectivity, loss of connection with neighbouring terrestrial habitats and loss of effective cleaning action; Baker et al., 2012; Weigelhofer et al., 2013). Point and diffuse discharges of toxic substances can also impair stream water quality and biotic communities (Archaimbault et al., 2010; Novotny, 2004; Usseglio-Polatera et al., 2001).

The European Water Framework Directive (WFD; European Council, 2000) does not only involve the assessment of the ecological status of water bodies but also the diagnostic of human activity impacts on water bodies. Consequently, it is necessary to provide practical guidelines to aquatic ecosystem managers for facilitating the design of efficient restoration strategies at the scale of coherent management units (e.g. the watershed and reach scales for streams). Although streams are subject to a large variety of significant driving forces and pressures, land use, eutrophication and habitat destruction have been clearly identified as the pressures exhibiting the greatest impacts (Stendera et al., 2012). Changes in land use, hydromorphology and physico-chemistry have already been linked individually to variations in biotic indices based on the taxonomic and/or functional characteristics of assemblages of macrophytes, diatoms, fish and macroinvertebrates (Dahm et al., 2013; Feld, 2013; Marzin et al., 2012; Sponseller et al., 2001; Sundermann et al., 2013; Villeneuve et al., 2015; Wasson et al., 2010). These studies have demonstrated that the links between pressures and biological indices are influenced by the spatial scale at which each pressure is taken into account (Allan, 2004; Allan et al., 1997; King et al., 2005; Lammert and Allan, 1999; Roth et al., 1996). Thus, watershed, hydromorphological reach and riparian corridor are spatial scales that considerably structure the effects of anthropogenic pressures on the ecological status of rivers observed as site scale (see also Marzin et al., 2012; Wasson et al., 2010). Shortly, the previous works have evidenced (i) the significant response of biotic indices to environmental variables characterizing gradients of nutrients, organic matter, hydromorphological pressures and land use at the watershed scale, (ii) the similarity of the core response pattern of all these biotic indices, but (iii) some between-indices differences in responses to specific pressure types, mainly regarding hydromorphology. Nevertheless, most of the time, the factors related to hydromorphological alteration have been ranked only at the third place (in order of decreasing importance of stream ecological status drivers) after physico-chemical and land-use factors. Both Dahm et al. (2013) and Villeneuve et al. (2015) have shown that the effects of hydromorphological pressures on biotic assemblages could be measured, but their impact on the set of tested biological metrics was relatively low. In summary, it seems possible to predict and clearly explain the ecological status of streams on the basis of pressure descriptors. However, the pressure descriptors selected in previous works didn't specifically take into account the multiple nested spatial scales that structure both the anthropogenic pressures and the longitudinal functioning of streams.

The main objective of our study was to explicitly examine the importance of the nested spatial organization of streams on the links between anthropogenic pressures and stream ecological status, by building - and analysing the results of - a model based on the Partial Least Squares (PLS hereafter) path modelling method (Jakobowicz, 2007; Tenenhaus et al., 2005; Wold, 1982). This method was applied for simultaneously analysing the effects of latent variables (i.e. variables which are not directly observed but supposed to enter into the functioning of the streams under study: e.g. land-use, hydromorphological and physico-chemical pressures) on the ecological status of rivers synthetically measured in this study by the macroinvertebrate-based French biotic index for wadeable rivers [I_2M_2; (Mondy et al., 2012)], as an example of one of