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Modelling the spatial and seasonal variability of water quality for entire river networks: Relationships with natural and anthropogenic factors

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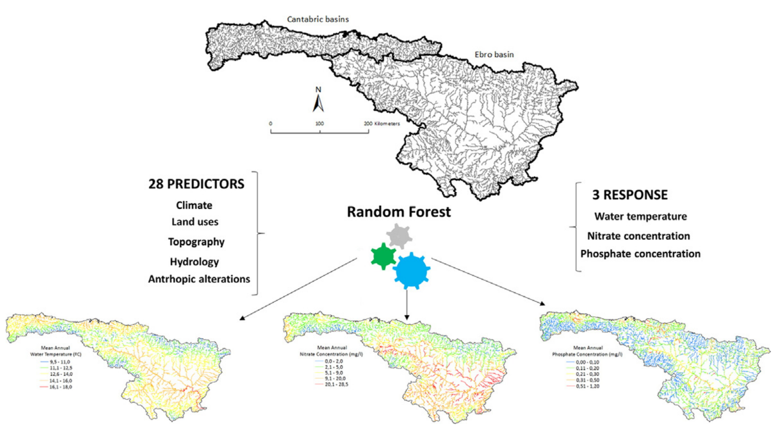
HIGHLIGHTS

- Water characteristics were modelled to whole river networks draining 110,000 km^2.
- Water characteristics were different on seasonal patterns and controlling factors.
- Air temperature, catchment area and forest cover controlled water temperature.
- Nitrates were higher in winter-spring and mainly related to agriculture land cover.
- Phosphates were higher in summer and mainly related to point sources.

GRAPHICAL ABSTRACT



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ABSTRACT

We model the spatial and seasonal variability of three key water quality variables (water temperature and concentration of nitrates and phosphates) for entire river networks in a large area in northern Spain. Models were developed with the Random Forest technique, using 12 (water temperature and nitrate concentration) and 15 (phosphate concentration) predictor variables as descriptors of several environmental attributes (climate, topography, land-uses, hydrology and anthropogenic pressures). The effect of the different predictors on the response variables was assessed with partial dependence plots and partial correlation analysis. Results indicated that land-uses were important predictors in defining the spatial and seasonal patterns of these three variables. Water temperature was positively related with air temperature and the upstream drainage area, whereas increases in forest cover decreased water temperature. Nitrate concentration was mainly related to the area covered by agricultural land-uses, increasing in winter, probably because of catchment run-off processes. On the other hand, phosphate concentration was highly related to the area covered by urban land-uses in the upstream catchment and to the proximity of the closest upstream effluent. Phosphate concentration increased notably during the low flow period (summer), probably due to the reduction of the dilution capacity. These results provide a large-scale continuous picture of water quality, which could help identify the main sources of change in water quality and assist in the prioritization of river reaches for restoration projects.

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1. Introduction

Water quality in fluvial ecosystems depends on different natural and anthropogenic factors that affect its catchment. Within the former group, the topographic characteristics are important. For instance, the slope is a determining factor in the transference of inorganic and organic compounds, such as phosphorus or nitrogen, from the soil to the channels (Villa et al., 2014). The orientation of the channels is another important topographic descriptor because it largely determines the solar radiation over the water surface and the temperature regime of rivers and streams (Caissie, 2006). In this regard, the variability of atmospheric temperature is also a major driver of water temperature. Changes in this variable produce important changes in the geographical distribution of aquatic species (e.g. Jonsson and Jonsson, 2011) and in the biogeochemistry of fluvial ecosystems (e.g. Couture et al., 2014). Another important climate variable is the precipitation regime. This variable governs the hydrologic regime of fluvial ecosystems and the catchment run-off processes (e.g. Sinha et al., 2014). Regarding the hydrologic regime and the hydraulic characteristics, Doherty et al. (2014) concluded that ponding facilitates the invasion and dominance of highly productive macrophytes (i.e. *Typha*), as well as the mobilization of phosphate compounds, in comparison with lotic environments, which support more diverse aquatic vegetation (mosses and algal mats) and cleaner water. Another natural factor widely analysed in relation to water characteristics is lithology, which determines, for example, the water alkalinity (pH) and conductivity and the concentration of different ions relevant to many biogeochemistry processes.

Regarding anthropogenic factors, the use of infrastructures for water supply, such as dams or weirs, produces changes in the natural hydrologic regime and the hydraulic characteristics of fluvial ecosystems, affecting the natural distribution of aquatic organisms and the export ratios of different organic and inorganic compounds (Seo et al., 2012). Moreover, changes in natural land-uses have been linked very often to changes in water quality. For example, the increase in the percentage of agricultural and urban land cover classes has been described as one of the greatest contributors to the increment of nitrate and phosphate concentrations in freshwater ecosystems worldwide. In contrast, catchments where natural uses dominate (e.g. forest) tend to keep water quality conditions unaltered (e.g. Tong and Chen, 2002; McDowell et al., 2011; Lowicki, 2012).

The high spatial and temporal variability of fluvial ecosystems hampers the physico-chemical characterization of water conditions at large spatial scales (i.e. whole river networks). Most catchment management plans are based on the assessment of water quality using field data from a few study sites. Commonly, these assessments are made only on a given river reach aiming to characterize the variability of a much larger water body. On many occasions, these evaluations only include information from one season (e.g. summer), losing the temporal variability of the different physico-chemical characteristics that determines water quality. Moreover, using field surveys to estimate the water quality from the many river reaches within a whole river network is unrealistic as the intensity and costs of those surveys would be prohibitive. The lack of continuous spatial and seasonal information on water quality characteristics makes it difficult to develop a large-scale picture of water quality (i.e. continuous values over a whole river network for different seasons). However, this framework could substantially improve the prioritization of effective management actions to improve water quality, especially these days when diffuse sources of pollution are becoming more important than point sources (Tong and Chen, 2002; King et al., 2005; Unwin et al., 2010). Data modelling in conjunction with field surveys might be an effective solution for covering this gap of information, as this approach allows the prediction of the seasonal variation of the different physico-chemical variables that characterize river water quality to all river reaches within a river network.

Most water quality models reviewed in the literature analyse the spatial variability of different water components in relation to natural (geology, climate and topography; Olson and Hawkins, 2012) or anthropogenic factors (mainly land use variables; King et al., 2005; Lowicki, 2012; Haidary et al., 2013; Delpla and Rodríguez, 2014) in a particular catchment. However, we have not found any study that combines both types of predictors to model water quality at large spatial scales. In this study, we used natural and anthropogenic factors to model the actual water quality in a large area that includes small to very large catchments (from 30 to 85,000 km^2) characterized by different climatic characteristics (Temperate and Mediterranean), land-uses and human development. Another novelty of this study is the seasonality of the proposed models. Most of the reviewed literature proposes water quality models for base-flow conditions (Olson and Hawkins, 2012) or taking together all the information collected in the study period, and thus, losing the effect of seasonality (Amiri and Nakane, 2006). Seasonal differences in water characteristics could be used to increase our understanding of how water quality impairment occurs and, thus, to design more effective restoration programmes.

In this study we developed a Virtual Watershed (sensu Barquín et al., 2015) to integrate the environmental information (natural and anthropogenic factors) of a large area (110,000 km^2) located in northern Spain (Europe) and to extract a wide variety of predictor variables. We used this digital framework to explore how natural and anthropogenic factors, acting at large (basin) and small (sub-basin or river stretch) spatial scales, affect water quality. Thus, the main objective of this study was to model the spatial and seasonal variability of 1) water temperature and the concentration of 2) nitrates and 3) phosphates for a whole river network. We chose these three variables because they are important descriptors of water quality, related to diffuse and point sources of pollution, and because they are also important drivers of river ecosystem biodiversity and functioning. Moreover, another objective of the study was to identify the most important environmental variables that govern the spatial and seasonal variability of these three physico-chemical water characteristics.

2. Methods

2.1. Study area

The study area (110,000 km^2) is situated in northern Spain (Europe) and includes river catchments managed by 3 different regional water agencies (Confederación Hidrográfica del Cantábrico: CHC, Agencia Vasca del Agua: URA and Confederación Hidrográfica del Ebro: CHE). The study area can be segregated into two large territories in relation to the environmental conditions (Fig. 1).

1. The first one drains into the Cantabric Sea, Atlantic Ocean, and is managed by CHC and URA. This territory is composed of small-medium catchments, ranging from 30 km^2 to 5000 km^2, which are characterized by their high slope and short length (Álvarez-Cabria et al., 2011A). In this area (25,000 km^2) climate varies from thermo-temperate Atlantic climate on the coast, to an oro- and supra-temperate climate in the inner regions (Rivas-Martínez et al., 2004). Precipitation is abundant throughout the year with a mean annual value of 1300 mm. Snow precipitation is frequent in high mountain areas in winter. Deciduous forest, scrubs and grasslands occupy 80% of this area, while agricultural land-uses only reach 10%. The mean population density is 100 inhabitants/km^2.

2. The second territory is occupied by the Ebro catchment and drains into the Mediterranean Sea (managed by the CHE; Fig. 1). This area covers a surface of 85,000 km^2 with an average of 32 inhabitants/km^2. This area is characterized by a Mesomediterranean and Supramediterranean climate (Rivas-Martínez et al., 2004), with a mean annual precipitation of 650 mm, varying from 300 mm in the central area of the main fluvial axis, to 1700 mm in the Pyrenees mountain range, where snow is abundant in winter and early spring