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Fuzzy modelling to identify key drivers of ecological water quality to support decision and policy making

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A B S T R A C T

Water quality modelling is an effective tool to investigate, describe and predict the ecological state of an aquatic ecosystem. Various environmental variables may simultaneously affect water quality. Appropriate selection of a limited number of key-variables facilitates cost-effective management of water resources. This paper aims to determine (and analyse the effect of) the major environmental variables predicting ecological water quality through the application of fuzzy models. In this study, a fuzzy logic methodology, previously applied to predict species distributions, was extended to model environmental effects on a whole community. In a second step, the developed models were applied in a more general water management context to support decision and policy making. A hill-climbing optimisation algorithm was applied to relate ecological water quality and environmental variables to the community indicator. The optimal model was selected based on the predictive performance (Cohen's Kappa), ecological relevance and model's interpretability. Moreover, a sensitivity analysis was performed as an extra element to analyse and evaluate the optimal model. The optimal model included the variables land use, chlorophyll and flow velocity. The variable selection method and sensitivity analysis indicated that land use influences ecological water quality the most and that it affects the effect of other variables on water quality to a high extent. The model outcome can support spatial planning related to land use in river basins and policy making related to flows and water quality standards. Fuzzy models are transparent to a wide range of users and therefore may stimulate communication between modellers, river managers, policy makers and stakeholders.

1. Introduction

Deterioration of water quality has become an issue of global concern (UN, 2014). The expansion of industries, agriculture, and tourism often causes water quality degradation (Goethals and Volk, 2016; Teixeira et al., 2014). Impacts on surface and groundwater resources limit their use for drinking, bathing, industrial, or agricultural purposes (UN, 2014). Furthermore, polluted water threatens both quality of life and public health (Barnhoorn et al., 2015; Hauck et al., 2015). Thus, conservation and restoration of good water quality are important. Monitoring, assessment, modelling and implementation of appropriate management actions are necessary to avoid further deterioration of water quality (He et al., 2014).

Water quality modelling is an effective tool to investigate, describe and predict the ecological state of the aquatic ecosystem. In the last decade, several methods were applied to model environmental systems. One of the most promising modelling approaches is fuzzy models (Zadeh, 1965), which are based on fuzzy set theory (Akerkar and Sajja, 2010). An advantage of fuzzy models is its flexibility, transparency and user friendliness (Adriaenssens et al., 2006; Akerkar and Sajja, 2010). These models take into account the inherent uncertainty of ecological variables and allow the expression of non-linear relations between

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ecological variables. A fuzzy rule-based system was constructed that connects the input variables to the output by means of if-then rules. Fuzzy models use linguistic descriptions such as 'low', 'moderate' or 'high' for the quantification of variables and transform these descriptions into a mathematical framework in which data processing can be performed (Kampichler et al., 2000). As such, fuzzy models have the ability to convey a logical and reliable stream of information (Adriaenssens et al., 2004). Furthermore, fuzzy models enable the incorporation of ecological aspects such as the ecological gradient theory (Cadenasso et al., 2003; Yarrow and Salthe, 2008).

Most of the developed fuzzy models have been used for assessment of ecosystem sustainability (Canavese et al., 2014; Liu et al., 2012), environmental impact assessment (de Siqueira et al., 2006; Peche and Rodríguez, 2011), development of water quality index (Gharibi et al., 2012; Icaga, 2007), development of environmental quality index (Peche and Rodríguez, 2012), water quality assessment (Liu and Zou, 2012; Scannapieco et al., 2012) and habitat suitability and prediction of organisms' occurrence (Adriaenssens et al., 2006; Mouton et al., 2011). These studies illustrate the potential of fuzzy models in ecological modelling, particularly in analysing and predicting ecological water quality.

The physicochemical and hydromorphological aspects of an aquatic ecosystem influence water quality and the occurrence of certain organisms (Alvarez-Mieles et al., 2013; Mereta et al., 2012). Various environmental variables may simultaneously cause water quality deterioration; however, selection of a limited number of relevant variables is essential to delineate management priorities and facilitates water resource restoration and conservation in a cost-effective way. Thus, input variable selection plays an important role in the development of data-driven models in environmental modelling (Li et al., 2015).

This paper aims to diagnose the major environmental variables predicting ecological water quality through the application of fuzzy models. Furthermore, an insight on the interactions of variables and the significance of different variables determining the water quality was examined. Model reliability was evaluated based on model's predictive performance and ecological relevance. A sensitivity analysis was performed as an extra element to evaluate the reliability and performance of the optimal model. Although the methodology was previously applied to predict species distributions in other river systems, in this study, the methodology was extended to model a whole community indicator and was applied in water management and policy making. In this paper, a case study is presented in modelling the ecological water quality in a single tropical river basin. However, the approach could be applied to other river basins as decision support in water management due to its simplicity, universality and transparency.

2. Materials and method

2.1. Study area

The Guayas River basin is located in central-western Ecuador and is one of the largest river systems in South America (Fig. 1). It occupies a land surface area of 34,000 km^2. The Daule Peripa dam is located in the Guayas River basin and covers an area of 18,000 ha (Arriaga, 1989). The Guayas River, with a total length of 60 km,

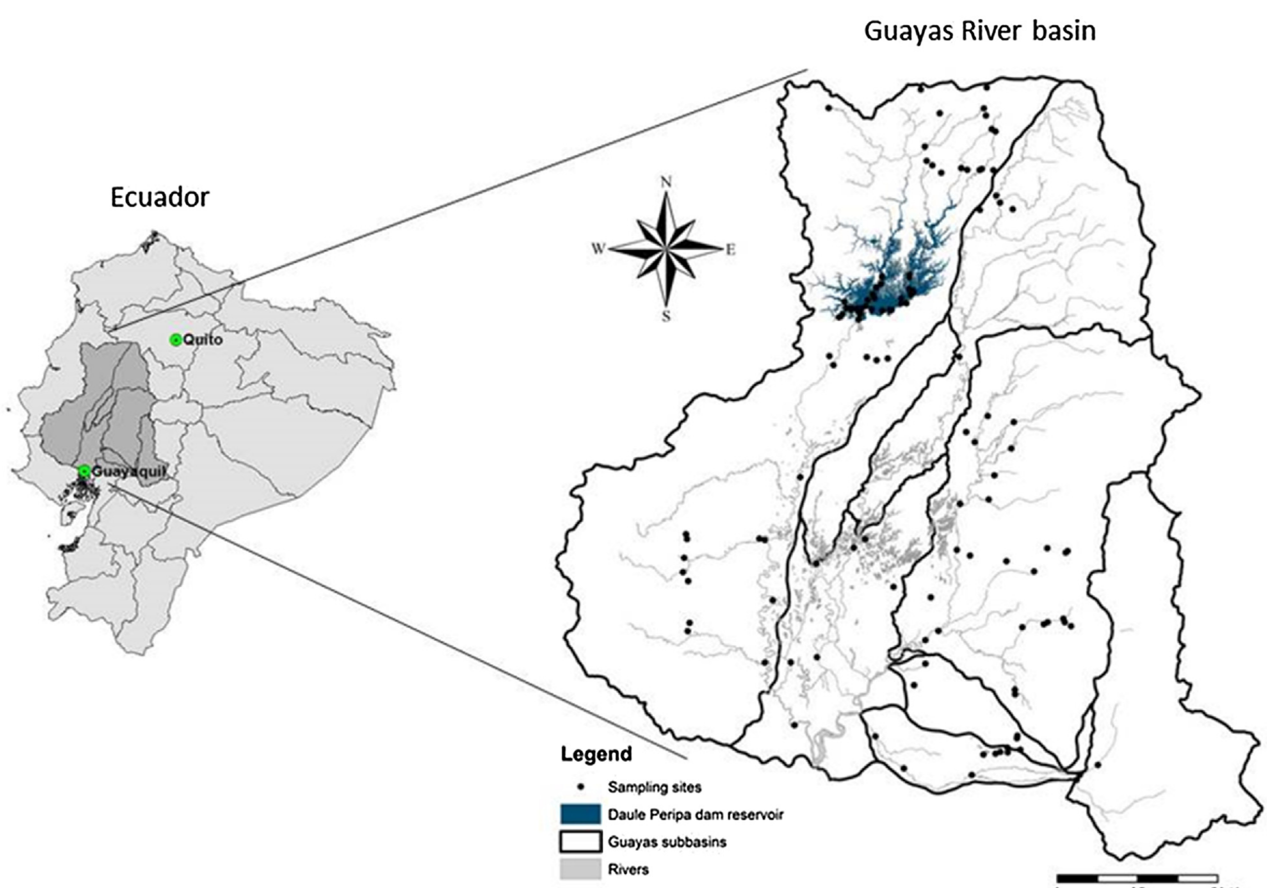

Fig. 1. The sampling sites at Guayas River Basin. The main rivers and the Daule Peripa dam within the basin are represented.