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Impact assessment of agricultural driven stressors on benthic macroinvertebrates using simulated data

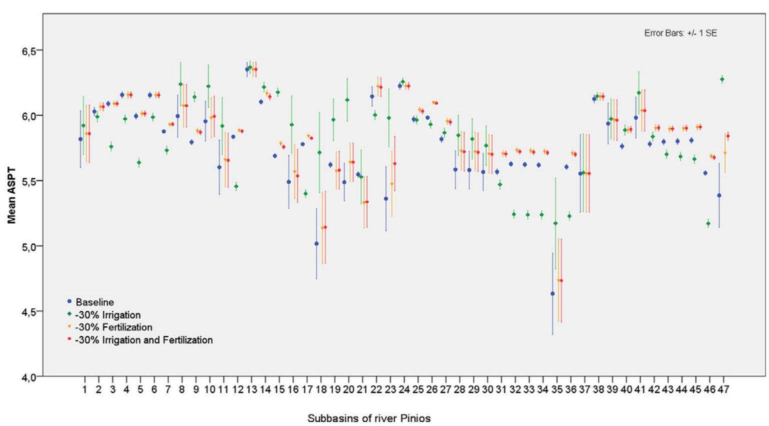
K. Stefanidis *, Y. Panagopoulos, M. Mimikou

Laboratory of Hydrology and Water Resources Management, Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens (NTUA), 5, Iroon Politechniou Street, 15780 Zografou, Athens, Greece

HIGHLIGHTS

- We linked a biotic metric (ASPT) with the output of a process based model
- We investigated the ASPT response to the application of three management scenarios
- Reduced fertilization improved the nitrogen concentration and ASPT values
- Reduced irrigation did not have any effect on water quality but saved water
- The combination of both scenarios would be the best management practice in our case

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural land use poses a significant threat to the ecological integrity of rivers in Europe. Particularly in the Mediterranean, water abstraction and nutrient application are anthropogenic pressures that have a significant impact on aquatic habitats and biodiversity. In this article, we assessed the effects of agricultural management practices on benthic macroinvertebrates in a large river basin of central Greece using simulated data based on the application of SWAT (Soil Water Assessment Tool) model. Physicochemical and hydrological output variables of the model were used as predictors of the ASPT (Average Score Per Taxon) metric based on a correlated component regression analysis (CCR) built on empirical data. The estimation of ASPT was performed for the wet and dry seasons within a 20-year period for a total of 47 subbasins under the baseline conditions and after implementing three management scenarios that reduced: a) irrigation water applied to crops by 30%, b) chemical fertilization applied to crops by 30% and c) both irrigation and fertilization by 30%. The results revealed that application of the reduced irrigation resulted to a slight increase of the simulated dissolved inorganic nitrogen concentration (DIN), which in turn decreased the mean ASPT in 21 of the 47 subbasins implying a negative effect on the macroinvertebrate communities. On the contrary, the reduction of fertilization as well as the combined scenario decreased both the simulated DIN and phosphate concentration causing an increase of the mean ASPT for a total of 40 of the 47 subbasins. Based on these results, we suggest that the best management

* Corresponding author.
E-mail address: kstefani@chi.civil.ntua.gr (K. Stefanidis).

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option is a combined practice of deficit irrigation and fertilization reduction since it improved water quality, increased ASPT values and saved a considerable amount of water. Overall, this work demonstrates a simple methodology that can efficiently assess the effects of agricultural management practices on biotic indicators.

1. Introduction

Streams and rivers are among the most threatened ecosystems in Europe due to the combined effects of multiple pressures related to anthropogenic activities (Schinegger et al., 2012). Nutrient pollution, habitat fragmentation, bank erosion and alteration in hydrology are some of the most common problems that riverine systems are facing today (Milly et al., 2005; Ormerod et al., 2010; Vörösmarty et al., 2010). Particularly in the Mediterranean region, changes in hydromorphology along with increased nutrient loadings are known to heavily influence both the ecological integrity and the aquatic biodiversity of rivers (Gasith and Resh, 1999; Bonada and Resh, 2013; Hershkovitz and Gasith, 2013). Human activities such as water abstraction, flow regulation, water diversion and nutrient application pose a significant threat to the functionality and structure of river ecosystems. To prevent further deterioration and improve the ecological quality of water bodies effective mitigation and restoration actions are needed (Aguiar and Ferreira, 2005; Hooke, 2006). Implementing such actions is mandated by the Water Framework Directive (WFD) through the development of specific river basin management plans (RBMPs) for each River Basin District (WFD CIS, 2003). However, the fulfillment of such actions requires first to understand how the aquatic biota, and specifically the biological quality elements (BQEs, fish, macroinvertebrates, benthic diatoms and aquatic macrophytes) according to the WFD, respond to anthropogenic pressures and to further explore the interactions between ecosystem traits under various multiple pressures.

Predictive models offer the potentiality to forecast changes in the ecology of aquatic ecosystems caused by numerous anthropogenic activities and as such they can act as helpful and effective tools in modern ecology for assessing and averting the impact of harmful effects (Carlisle and Meador, 2007; Jähnig et al., 2012; Maloney et al., 2012). However, modeling the complex interactions between biotic and abiotic elements such as hydrological and hydraulic traits is not an easy task and there is still a lack of models that can fully describe the links between the aquatic organisms and their environment (Einheuser et al., 2013). Several studies have proposed the use of habitat models that can link the local hydraulic conditions and the preference of organisms to these conditions. These models are used to predict the effects of pressures, e.g. changes in discharge, on the aquatic hydraulic habitat and therefore estimating the impact on the aquatic organisms. However, the majority of these models was mostly developed for using fish as a target organism group and therefore may not be accurate and effective for other organisms, namely the benthic macroinvertebrates. More recently, species distribution models (SDMs) have been applied in freshwater ecosystems in order to identify the responses of aquatic organisms under the pressures derived by the climate change. Most applications of these models at freshwater ecosystems are broad scale studies that do not address the implementation of management measures at local scale (Kuemmerlen et al., 2014). Moreover, the effectiveness of SDMs highly depends on the detail and quality of the data required such as the occurrence and abundance of specific species.

An alternative approach that has been proposed to study these complex interactions is the use of simple regression models that can be easily developed and applied in cases where data are limited. There are numerous studies in the field of river ecology that have used effectively various regression techniques such as multiple linear regression analysis, general additive models, multivariate approaches, regression tree analysis, artificial neural networks and fuzzy logic methods (Clarke et al., 2003; Buffagni et al., 2006; Carlisle and Meador, 2007; Gabriels et al., 2007; Weigel and Robertson, 2007; Pool et al., 2010; Marchini, 2011). More recently, Einheuser et al. (2013) applied various regression methods, including stepwise linear regression, partial least squares and fuzzy logic, in order to develop predictive models that estimate the biological integrity of a large river basin using as descriptors output variables of the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998).

Based on this approach, the purpose of this article is to develop robust regression formulae to be used as user-friendly statistical models, to calculate benthic macroinvertebrate metrics from in-stream hydrological and physicochemical data. Our approach is based on an integrated process-based modeling with the extensively applied SWAT river basin model (Gassman et al., 2014), and uses the physicochemical output variables of the model as river descriptors for predicting the responses of macroinvertebrate variables. We decided to use macroinvertebrate metrics as target response variables for two reasons. Benthic invertebrates are considered an ideal group of organisms for assessing the ecological quality of rivers because of their sensitivity to changes in properties of water quality and aquatic habitat (Feld and Hering, 2007; Skoulikidis et al., 2009). Combined with the fact that their sampling and identification methodology is relatively easy and cost effective (Clarke et al., 2003), benthic macroinvertebrates are commonly used as bioindicators to detect the impact of human pressures on river ecosystems. The other reason is practical and has to do with the data availability and the fact that we have at our disposal a solid empirical dataset provided by the Greek Ministry of Environment and previous published studies that have been carried out in the area of interest (Chatzinikolaou, 2007; Chatzinikolaou et al., 2010).

The methodology is developed in a Greek agricultural catchment, where water scarcity and nitrate pollution are the major environmental threats, and the proposed approach is demonstrated both under the baseline conditions and the implementation of alternative management practices, with the purpose to provide predictions of benthic macroinvertebrate metrics under various management conditions.

2. Methods

2.1. Study area and process-based model setup

The Pinios basin covers almost entirely the River Basin District (RBD) of Thessaly in Central Greece (see Fig. 1). The 10,600 km^2 basin is an important agricultural area in Greece, with feed (corn, alfalfa) and industrial crop production (cotton). However, the crop growth periods are the dry periods (May to September) of the year and are accompanied with high temperatures, high evapotranspiration rates and dry soils (Vasiliades et al., 2011). Inevitably, these conditions result in irrigation cutbacks and overexploitation of both surface and groundwater resources with significant impacts on the natural water cycle and water availability, especially in the driest years. Intense agriculture and overfertilization in the region is also considered responsible for surface and groundwater quality degradation mainly in terms of nutrient concentration in waters (Bellos and Sawidis, 2005; Chatzinikolaou et al., 2010; Loukas, 2010). Recent environmental analyses in the area have shown that the likelihood of the Pinios basin's water bodies failing to achieve good ecological status is generally high (Ioannou et al., 2009).

In order to discover favorable mitigation options that address these important environmental issues, a detailed Pinios basin modeling system has been constructed and tested with the use of SWAT 2009 (version 488) and ArcSWAT interface (Panagopoulos et al., 2012;

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