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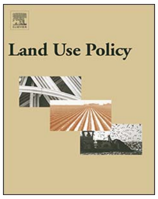

Anthropogenic nutrients and eutrophication in multiple land use watersheds: Best management practices and policies for the protection of water resources

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ABSTRACT

Blooms of cyanobacteria (*Microcystis aeruginosa*) are becoming increasingly recurrent in the A Baxe dam reservoir (Galícia, Northern Spain) as a result of increasing levels of different anthropogenic pressues in the Umia catchment. The aim of this study is to develop a model that allows us to detect the spatial level where the main problems that trigger eutrophication occur. We used Mike Basin coupled with Load Calculator to model and visualize spatially explicit results of stream flow and N and P export. The results indicate increase in nitrogen (N) and phosphorus (P) concentrations that trigger eutrophication.High concentrations of nutrients at the Upper Umia derive from livestock, while at the Lower Umia the origin is sewage, highlighting impacts from diffuse pollution and point source pollution in different areas of the basin. Cyanobacteria blooms result from the influence of both contaminant sources, being also triggered by local environmental conditions such as temperature, solar radiation or flow rate. This model will be useful for predicting possible changes, alterations and evolutions that occur in the watershed, that can help ensure compliance with the Water Framework Directive. In addition to the model developed, the results indicate the need for the implementation of management practices in order to reduce the blooms of cyanobacteria (green systems for wastewater in rural areas, riparian forest restoration, etc.). Some sub-basins, such as the Gallo sub-basin, require immediate action since they are major contributors of nutrients to the main river as a result of the low carrying capacity of local waste water treatment plants.

1. Introduction

Cyanobacteria are the most ancient phytoplankton on the planet and form harmful algal blooms (HAB) in freshwater, estuarine and marine ecosystems (O'Neil et al., 2012). HAB are proliferating worldwide mostly due to anthropogenic nutrient enrichment, and they represent a serious threat to the use and sustainability of our freshwater resources (Paerl et al., 2011). Nitrogen (N) and phosphorus (P) are the most important nutrients causing eutrophication that may trigger HAB, and therefore N and P input constraints are needed for a long-term control of HAB in surface water bodies. Anthropogenic nutrient-HAB link is not considered universal (e.g. Davidson et al., 2014), and hence any mitigation measure to be implemented has to consider site-specific control factors, namely flushing flows (Bowling et al., 2013), temperature (Gkelis et al., 2014), microbial grazers (Smayda, 2008), among others. Monitoring of HAB is mandatory in the EU countries for compliance with the Water Framework Directive (WFD), while guidance is provided in specific documents (e.g. JNCC, 2015).

High concentrations of nutrients derived from anthropogenic activities in water bodies may be ascribed to specific land uses (Lapointe et al., 2015; Vogt et al., 2015) or its intensity (Palmer-Felgate et al., 2009; Rowan et al., 2012). However, they are more frequently related to inadequate management practices at critical source areas of diffuse nutrients in catchments (Doody et al., 2012; Kovacs et al., 2012; Kurz et al., 2005a,b; Rodriguez et al., 2011; Strauss et al., 2007; among others).Reservoirs are an important resource of energy and drinking water, but very susceptible to impacts (Hughes et al., 2012). Therefore, the identification of critical source areas of diffuse nutrients is crucial to successfully predict eutrophication and HAB and select the correct decision-making in its prevention or mitigation. The WFD prescribes

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programmes of measures to fulfil pre-determined environmental objectives, including the control of diffuse pollution. These measures are to be drawn up according to “judgements about the most cost-effective combination of measures” (article 11 of the WFD). Cost-effectiveness analysis is proposed as the general framework for prioritising measures in application of the WFD (Balana et al., 2011). Some studies developed and applied spatially dynamic models to assess how anthropogenic impacts can influence on the quality and status of freshwater bodies at catchment scale (Hughes et al., 2016; Cabecinha et al., 2009, 2004). But in the present study we focus on the spatial modeling of anthropogenic nutrients and their relation to sources, eutrophication and HAB, especially in catchments with various anthropogenic pressures (agriculture, urbanization). There are a few studies on the assessment of eutrophication risk in contexts with scarce data (Dupas et al., 2015), using indices based on catchment and reservoir physical characteristics (Leigh et al., 2010), or based on Multicriteria Analysis (Hughes et al., 2005), but they do not correspond to spatial modeling of anthropogenic nutrients in watersheds affected by eutrophication and HAB. There are also numerous studies on the exports of N and P from catchments (Chen et al., 2015; Jackson-Blake et al., 2015; Lazzarotto et al., 2005; Lewis et al., 2013; Perks et al., 2015), but usually they do not specifically link spatial modeling of anthropogenic nutrients to identification of source areas in watersheds where recurrent algal blooms occur.

This paper presents a spatial modeling of nitrogen and phosphorus concentrations in the Umia watershed (Spain), a catchment severely affected by eutrophication and HAB, especially where the Umia River has been dammed forming the A Baxe lake. The modeled concentrations are based on the heterogenous spatial distribution of agricultural areas and discharge points of uncontrolled domestic sewage across the basin. After model calibration, the scaling of concentrations down to the subcatchment scale allowed visualization of major source areas of anthropogenic nutrients. A secondary objective of this study outlines a number of mitigation measures for reducing N and P exports towards the A Baxe Lake, following the concept of sustainable catchment management (e.g., Macleod et al., 2007).

2. Materials and methods

2.1. Study area

The study area comprises the Umia watershed, upstream of the A Baxe dam located in the region of Galicia, Northwestern Spain (Fig. 1). The Information System on Land Occupation in 2006 (SIOSE in Spanish) shows that forest covers 37% of the basin, scrubland 25%, grasslands and crops 37.4%, and artificial areas 0.6%. The Umia reservoir was built in 2000 representing a maximum capacity (maximum normal level) of 8.05 hm^3. The environmental flow regime was set between 2.1 $m^3 s^{-1}$ (from June to September) and around 3–4.5 $m^3 s^{-1}$ (from October to May) by an Environmental Impact Assessment, but the summer value is not met (Augas de Galicia, 2011). The total area of the river basin upstream of the reservoir is 440.4 km^2 while the average flow rate is 16.2 $m^3.s^{-1}$. The main tributary of the Umia is the Gallo River with a sub-basin area of 44.3 km^2. Both rivers are in the domain of Galicia-Costa District. Average rainfall in the region approaches 1400 mm while temperatures vary from 7 °C in January to 20.5 °C in July-August (Fig. 1). The watershed altitudes range from 99 m.a.s.l. in the reservoir area to 798 m in the Umia River headwaters.

The Umia basin has a high degree of population dispersion, characterized by a large number (184) of villages with no more than 500 inhabitants and mostly (68%) with less than 50 inhabitants (Fig. 2a). A total of 106 waste sites are listed in the basin (Augas de Galicia, 2011). According to the Spanish regulations on urban wastewater (Del Estado, 1996), quite a few (25%) of these sites are sources of contamination while others (15%) are known sources of pollution. Only a very low proportion of these sites (1%) was characterized as occasional discharge points. The main points of sewage discharge are located in the basin of the Gallo River (Fig. 2b). Existing waste water treatment plants are poorly maintained. Consequently, downstream reaches are usually characterized by high values of suspended solids, biochemical oxygen demand, and chemical oxygen demand. The highest density of farms is observed in sub-basins of the catchment headwaterds (Fig. 2b). Approximately 10,000 ha correspond to the so-called potential agricultural area (PAG) that includes pastures, meadows, forage crops and annual crops (SIOSE website, see address in Table 1). The PAG is mostly distributed around Estrada (37%), Forcarei (28%) and Cuntis (24%) villages (Fig. 2b). Production of livestock is among the most important agriculture activities, with poultry farms largely dominating over other cattle explorations (Table A1, in the Appendix).

In recent years, harmful algal blooms have become a persistent problem in the A Baxe dam lake. To deal with the problem the regional government has implemented a monitoring program for the water quality with a network of sampling stations (Fig. 2b), as well as an alarm system for the proliferation of cyanobacteria (*Microcystis aeruginosa)* in summer. The highest concentration of cyanobacteria was obtained in September 2010 with 248750 $cells.ml^{-1}$, while in 2009 there were no significant proliferations (Fig. 3).

2.2. Data requirements, sources and computational techniques

Mike Basin (DHI, 2013) was selected to handle the data and perform the modeling, because this software has been used with sucess in many hydrologic applications (Bangash et al., 2012; Sanches Fernandes et al., 2010; 2011, 2012, 2014). Mike Basin incorporates the Danish Nedbør-Afstrømnings-Model (NAM) to set up watershed rainfall-runoff relationships and the Load Calculator tool to estimate nutrient concentrations in river water. The NAM algorithm has modeled river flows under various weather conditions and hydrologic regimes (Madsen et al., 2002; Makungo et al., 2010; Santos et al., 2014; Zhu et al., 2008), while the Load Calculator has been considered accurate in the estimation of nutrient loads from diffuse and point sources (Zhu et al., 2008). The study used ArcGIS/ArcMap of ESRI (2010) to produce sophisticated thematic maps. The option for this software relates to the authors' experience on using this program in numerous hydrologic, decision making and environmental applications (Pacheco and Landim, 2005; Pacheco and Van der Weijden, 2012a,b; Pacheco and Van der Weijden, 2014a,b; Pacheco, 2013; Pacheco et al., 2013; Santos et al., 2015a,b).

Digital records on topography, climate, population density, land use, agriculture practices and water quality were among the databases used to complete the watershed modeling presented in this study (Table 1).

2.3. Modeling stream flows and river water quality

Prior to the calculation of N and P loads in the Umia River basin, a run of NAM model was required to set up calibrated river flows at the subcatchment scale. Detailed information and explanation on the mechanics of NAM is beyond the scope of this paper and can be found elsewhere, namely in the reports of Madsen et al. (2002) and Makungo et al. (2010). NAM input uses the basin's digital elevation model (DEM; Fig. 1) to define the local drainage network and associated catchments. Having defined a geometric framework for water flow, NAM processes time series of temperature and precipitation to obtain modeled river flows on a daily basis at catchment scale. Time series of stream discharge are also added to the algorithm with the purpose of comparing modeled with real flows (calibration/validation). In both cases the timeframe in this study comprised the period 2005–2010, which has been divided into the calibration (2005–2008) and validation (2009–2010) periods. Precipitation records were compiled from a number of udometric stations (Fig. 4). Before being used in the NAM, the daily rainfall values were averaged for the entire Umia River basin using the Thiessen's polygon method. Two stations provided data on temperature for the hydrologic modeling: Pereira and Caldas de Reis,