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A protocol to prioritize wetland restoration and creation for water quality improvement in agricultural watersheds

Francisco A. Comín[a,*], Ricardo Sorando[a], Nadia Darwiche-Criado[b], Mercedes García[a], Adriá Masip[c]

[a] *Instituto Pirenaico de Ecología-CSIC, Av. Montañana 1005, 50192 Zaragoza, Spain*
[b] *Instituto Pirenaico de Ecología-CSIC, Av. de la Victoria s/n, 22700 Jaca, Huesca, Spain*
[c] *Parque Científico-Tecnológico Aula Dei, Av. Montañana 930, 50059 Zaragoza, Spain*

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ABSTRACT

With adequate planning, wetland restoration and creation can be useful tools for improving the water quality of natural ecosystems in agricultural territories. Here, a protocol for selecting wetland-restoration sites at the watershed scale is proposed as part of a demonstration project (EU Life CREAMAgua) for improving wastewater from irrigated agricultural land discharging into the Flumen River (Ebro River Valley, NE Spain). This watershed is semiarid, and 70% of its 1430-km^2 area is used for irrigated agriculture. A preliminary study of the physical and chemical characteristics of the Flumen River and its watershed identified nitrates as the key water-quality characteristic in terms of data variability. The protocol consisted of five steps that encompassed scientific–technical, social and economic criteria. The first step was to select all of the sites in the watershed that had the hydrogeomorphic characteristics of a wetland. The second step was to estimate the levels of nitrate discharge through all of the tributaries discharging to the river and to select the sub-watersheds that contributed the most nitrates. The program SWAT (Soil and Water Assessment Tool), which considers the biophysical characteristics and land uses of the watershed, including farming practices, was utilized in these first two steps. In the third step, a first-order area-removal model was used to rank wetlands for nitrate removal. The wetland sites that were estimated to be most efficient for nitrate removal were selected. These wetland sites were located in the agricultural zone within the watershed, where fertilizers and irrigation are intensively used. In the next step, the previously selected sites were considered based on a social-availability criterion (the potential to obtain at no cost the land required to restore or create wetlands at those sites). Finally, the concordance between site availability and funding was used to sequentially select 15 sites (135 ha) that would be cost-effective for the Flumen River watershed project, which provided a case study. This protocol is compared to previously published protocols with the same purpose, and the applications of this procedure are discussed in terms of up-scaling and integrating experience in land-use and agricultural policies.

1. Introduction

Interest in developing methodology for wetland restoration at the watershed scale has increased during recent years. Wetland-restoration researchers have increasingly recognized that first, they must plan the recovery of a huge amount of wetlands degraded or lost during the last century; and second, wetland restoration is more efficient if considered at the landscape scale (Verhoeven et al., 2006; Moreno-Mateos and Comin, 2010). For example, wetland restoration has been proposed to restore the nutrient-removal function of wetlands in the Mississippi–Missouri watershed (Mitsch and Day, 2006). Wetland restoration has been practiced at different scales, from small (Richardson et al., 2011) to large watersheds (Chimney and Goforth, 2006). Indeed, wetland restoration at the landscape scale has been proposed as the most effective approach to improve the water quality within watersheds (Bedford, 1999; Zedler, 2003; Crumpton, 2001).

One of the major environmental challenges for agricultural development is to increase production while decreasing the impacts of pollutants on the water quality of aquatic ecosystems (Tilman et al., 2002). Restoring and creating wetlands at the watershed scale has been suggested as a general strategy to accompany

* Corresponding author at: Campus Aula Dei, Instituto Pirenaico Ecología-CSIC, Av. Montañana 1005, 50192 Zaragoza, Spain. Tel.: +34 976 392019; fax: +34 976 363222.
E-mail addresses: comin@ipe.csic.es, darwiche@ipe.csic.es (F.A. Comín).

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sustainable agricultural development by buffering the impacts of non-point-source pollutants on aquatic ecosystems (Mitsch et al., 2001; Zedler, 2003). Changes in agricultural practices as adequating the fertilizer rates to the plant requirements both in time and doses are necessary to reduce nutrient losses from farming uses to the state that there are no further avoidable nutrient losses. Then, integrating wetland restoration and creation into sustainable land uses and land cover planning would recover the ecosystem services and economic benefits that wetlands provide at the watershed scale (Jenkins et al., 2010). Therefore, protocols for planning wetland restoration and creation at the watershed scale are needed for land-use management and ecosystem conservation and restoration. Also there are general statements in the European legislation to improve the water quality of natural surface waters through both limiting the emission of contaminants as a consequence of water uses in the watersheds and establishing controls to avoid contaminant discharges into natural ecosystems, as well as specific suggestions to restore and create wetlands as a measure to improve the water quality and the ecological status of natural aquatic ecosystems (EU Parliament and Council, 2000).

However, a simple and unique protocol for planning wetland restoration and creation at the watershed scale is difficult to obtain because watersheds and land and water uses differ greatly among regions and societies. A landscape approach analyzing the relationships among landscape, wetland and watershed characteristics was suggested as a general approach to establish restoration priorities at the watershed scale (Bohn and Kershner, 2002). This approach was used to select appropriate sites for restoring and creating wetlands in watersheds (Lesta et al., 2007; Martín-Queller et al., 2010). Another landscape approach, relating the land-use and morphological characteristics of river networks to water-quality data, was used to analyze the relationships between wetland characteristics and particular water-quality characteristics, such as phosphorus removal (Weller et al., 1996). A general protocol to restore and create wetlands for water-quality improvement at the watershed scale was proposed based on optimizing a proxy variable for water-quality improvement, the water-residence time in the wetlands (Almendinger, 1999). The same approach was used to predict nitrogen retention in several potential restored wetlands under three different nitrogen-removal models (Trepel and Palmieri, 2002). Newbold (2005) used an 8-step algorithm combining hydro-ecological modeling and experience-based restoration costs to prioritize sites for wetland restoration by optimizing the benefit–cost criteria.

This paper presents a protocol that integrates previous approaches to restore and create wetlands for the improvement of water quality at the watershed scale. This protocol consists of a greedy algorithm incorporating the three aspects (scientific–technical, economic, social) of ecological restoration (Comín et al., 2005).

2. Materials and methods

The Flumen River watershed (1431 km^2), located in the Ebro Basin (NE Spain), is a semiarid region with high inter-annual rainfall variability (150–400 mm/yr) and high potential evapotranspiration (900–1200 mm/yr) (Fig. 1). The average water discharge of the Flumen River (5 Hm^3/yr) is not sufficient to meet the water demand for agricultural irrigation in this watershed (800 Hm^3/yr). The intense agriculture that occupies most of the middle and lower parts of the Flumen River watershed is irrigated with water transported by a dense network of canals from two other rivers, Cinca and Gallego, located to the east and west of the Flumen River basin, respectively. Another dense network of drainage canals collects excess water from irrigated fields (March–October) into larger canals and finally drains into the Flumen River through natural gullies in the lower parts of every sub-watershed.

A preliminary survey of the water quality of the Flumen River was performed to determine differences between water characteristics in different parts of the river. Water samples were collected bimonthly during 2009–2010 at several points along the Flumen River and its tributary. Some variables (temperature, specific conductivity at 25 °C, pH, dissolved oxygen) were recorded in situ with calibrated electronic equipment. Samples of running surface water were collected directly from the river in polyethylene bottles and stored (24 h) in cold conditions (4 °C). Analysis of alkalinity (no filtrated water), major dissolved ions, and different forms of nitrogen and phosphorus were performed following standard methods (APHA, 2012).

The program SWAT (Soil and Water Assessment Tool) was used to model water flow and nitrate discharges in each sub-watershed draining into the Flumen River during 2006–2009. Data on water and nitrogen used as fertilizer for various agricultural uses were obtained from interviews with selected farmers. Maps of land use, soil type, elevation (from a digital elevation model), terrain slope, and climatic characteristics required for SWAT modeling were obtained from official mapping agencies (CHE-Confederación Hidrográfica del Ebro) SWAT modeling begins by defining Hydrologic Research Units (homogeneous hydrologic areas within the region), which were aggregated to form sub-watersheds here.

Based on the climatic and other data sets listed above, monthly water flows were estimated using SWAT for the whole Flumen River watershed and calibrated using a two-year dataset recorded continuously with an automatic sampler placed at the lowest reach of the Flumen River. This model was then employed to estimate monthly and annual water and nitrate discharges for each of the 163 sub-watersheds discharging to the Flumen River.

The greedy algorithm presented here to prioritize sites for wetland restoration and creation in agricultural watersheds consists of several successive steps integrating scientific–technical (hydrogeomorphic, biogeochemical, morphological), social and economic criteria (Fig. 2).

(1) The first step is to delineate potential areas of the watershed for wetland restoration and creation. SWAT modeling can delineate all of the sub-watersheds through which water flows to the river. There is at least one potential site for wetland restoration or creation in the lowest part of each sub-watershed, where water draining into the Flumen River forms sediment deposits covered with emergent vegetation. The lowest reach of each stream collects water from the entire sub-watershed and discharges the water, with the pollutants that it carries, into the river. Thus, these are the sites within each sub-watershed where a wetland is most likely to improve the quality of the water discharged into the river. In-stream wetlands are already present at these sites, making them suitable areas for wetland restoration (Martín-Queller et al., 2010). Additionally, old maps showing the former wetland distribution in the region can be overlapped with the digital elevation map to identify low-elevation areas not directly connected to the drainage network where off-stream wetlands could be restored or created (Moreno-Mateos et al., 2010).
(2) The second step is to select among the previously delineated potential sites based on their nitrogen loads. SWAT modeling estimates the water flows and nitrate concentrations in each sub-watershed. Sub-watersheds that drain agricultural areas will discharge larger amounts of nitrate than those that do not. For a simple sub-watershed discharging directly to the river, nitrate removal can be effected by a single wetland located