Ecological Engineering 103 (2017) 426–435

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Effects of wetland restoration on nitrate removal in an irrigated agricultural area: The role of in-stream and off-stream wetlands

Nadia Darwiche-Criado[a,b,*], Francisco A. Comín[a,b], Adrià Masip[a,b], Mercedes García[a,b], Silvia G. Eismann[a,b], Ricardo Sorando[a,b]

[a] Instituto Pirenaico de Ecología-CSIC, Av. Victoria s/n, 22700 Jaca, Huesca, Spain
[b] Instituto Pirenaico de Ecología-CSIC, Av. Montañana 1005, 50059 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form 8 March 2016
Accepted 9 March 2016
Available online 17 March 2016

Keywords:
Wetlands
Nitrate removal
In-stream
Off-stream
Seasonality
Irrigation

ABSTRACT

Eleven in-stream and five off-stream wetlands were restored in the southern portion of the Flumen River basin, an intensively irrigated agricultural area located in NE Spain, to evaluate their efficiency for nitrate removal and to assess the factors affecting their performance. Samples were taken during different periods of the year during 2011–2014 to evaluate the influence of agricultural activities during the two years following their completion. Nitrate concentration was significantly higher in the in-stream wetlands, showing a clear dilution effect caused by the inputs of the irrigation return flows. The patterns followed by the first-order nitrate removal rate constant were different for in-stream and off-stream wetlands and during irrigation and non-irrigation seasons. During non-irrigation seasons, the nitrate outflowing concentration was found to be negatively correlated ($p < 0.01$) to the first-order nitrate removal rate constant for in-stream wetlands, indicating that high nitrate inputs may restrict the effectiveness of the wetlands. Temperature and dissolved oxygen were also found to significantly influence the performance of off-stream wetlands during non-irrigation seasons, but only dissolved oxygen promoted the nitrate removal during the irrigation period, indicating the influence of the seasonal factor on nitrate and wetlands dynamics. The results of this study showed that although a longer time is required to achieve optimal wetland development, wetlands can be used as buffer zones that effectively remove nitrates. This study emphasizes the influence of the agricultural seasonality of the factors affecting nitrate removal in wetlands, expanding the information provided by similar studies and validating a model that is applicable to a wide range of agricultural, hydrological and seasonal conditions.

1. Introduction

Agricultural land use is a primary contributor to the degradation of water quality (Lenat and Crawford, 1994; Tong and Chen, 2002) and the primary source of nitrogen in European aquatic environments (Grizzetti et al., 2005). The excessive use of mineral fertilizers and the disposal of manure cause irrigation agriculture to be one of the primary nutrient sources worldwide (Baker, 1992). Due to the intensive use of nitrogen as fertilizer to increase crop productivity, dissolved nitrogen is discharged as nitrates (e.g., NO_3^-) into the water discharged from irrigated fields and is a major pollutant where intensive agricultural irrigation is performed (Vitousek et al., 1997; Turner et al., 2003). The threat of pollution from this source necessitates both global and local solutions for developing sustainable agriculture (Tilman et al., 2011).

Recent studies recommend the restoration of wetlands at the watershed scale to recover natural wetland functions, which include the improvement of non-point source pollution (Zedler, 2003). Wetland systems have been designed and evaluated for their ability to improve the water quality of agricultural discharges (IWWR, 2003; Vymazal, 2010). Planning the restoration and construction of wetlands for non-point source NO_3^- removal in agricultural regions requires measuring the potential of the wetlands in every geographical setting because wetland performance is highly dependent on the specific characteristics of both the land and the wastewater requiring treatment (Kadlec and Wallace, 2009).

Several factors have been shown to influence the denitrification processes in wetlands. The description of these factors based on environmental conditions is essential to optimize the performance

---

[*] Corresponding author at: Instituto Pirenaico de Ecología-CSIC, Av. Victoria s/n, 22700 Jaca, Huesca, Spain.
E-mail addresses: darwiche@ipe.csic.es, nadiadarcri@hotmail.com (N. Darwiche-Criado).

http://dx.doi.org/10.1016/j.ecoleng.2016.03.016

of a wetland to retain NO_3. In this regard, because denitrification is a biological process, several authors have described the effects of temperature and dissolved oxygen (DO) on nitrogen transformations (Phipps and Crumpton, 1994; Vymazal, 2007).

Based on its position with respect to a river or stream flow, a wetland can be considered to be "in-stream" (i.e., located in a stream or river channel) or "off-stream" (i.e., located outside of a stream or river channel). Restoring and constructing in-stream and off-stream wetlands can provide an opportunity to control non-point source pollution, regulate water storage, and develop habitats for both aquatic and non-aquatic species. Using in-stream wetlands to buffer non-point source discharges requires storing water in a river channel for extended periods if it is to significantly reduce the pollutants discharge from irrigated agricultural fields. This means detaining the water through the artificial wetlands. However, sometimes this type of wetlands cannot fully treat drainage water during runoff events or the land available is limited in intensive agriculture areas. In these cases, an alternative solution is proposed creating an off-stream wetland (Tournebize et al., 2013). For off-stream wetlands, water from a river or stream channel must be moved to the site where the off-stream wetland is located for flooding; with this system, large areas can be used to remove pollutants (Gannon et al., 1995; Gilliam et al., 1997; Knox et al., 2008) (Fig. 1).

In this study, 11 in-stream and 5 off-stream wetlands were restored in the southern Flumen River basin, an agricultural territory with intensive irrigation. NO_3^- comprises most of the nitrogen discharged through the irrigation return flows in the study area (Martín-Queller et al., 2010; Comín et al., 2014) and is the most common target for water quality improvement, in addition to being particularly important in the study region (Causapé et al., 2006; Lassaletta et al., 2009; Abrahão et al., 2013). Similarly, agricultural seasonality has a significant influence on the NO_3^- transport in this area (Darwiche-Criado et al., 2015a).

The objectives of this study were (1) to assess the factors involved in removing NO_3^-, and (2) to evaluate the role of two types of restored wetlands (i.e., in-stream and off-stream) in this process. In addition, (3) we assessed the influence of two agricultural periods (i.e., irrigation and non–irrigation) on the wetlands efficiency due to their importance in the study area (Darwiche-Criado et al., 2015a, 2015b), and to guide the restoration objectives in the future.

2. Materials and methods

2.1. Wetlands restoration and monitoring

The study area is located in north-eastern Spain (Fig. 2) in the Flumen River basin (1430 km^2). The climate conditions in this region are semi-arid with an average annual rainfall of 581 mm y^{-1} (Pedrocchi, 1998). 11 in-stream and five off-stream wetlands were restored in different sub-watersheds in 2011, 2012 and early 2013 to demonstrate their potential to improve the water quality and biodiversity of agricultural catchments following the EU CREA-MAGUA Life Project. Wetland restoration was performed in the southern part of the watershed, whose principal land use is irrigated agriculture. Irrigation runs from April to October, but the summer months are those with the greatest irrigation activity. Water discharge is typically higher during the irrigation season due to the contribution of the irrigation runoff, also affecting to the River water composition (Darwiche-Criado et al., 2015b).

Before starting any restoration activities, preliminary samplings in the Flumen River basin were performed to determine a baseline characterization of the water quality in the region. The SWAT (Soil and Water Assessment Tool) program was also used to model the water flows and NO_3^- discharges in each sub-watershed draining into the Flumen River during 2006–2009. The sites chosen for wetland restoration and creation in agricultural watersheds were identified based on scientific and technical (i.e., hydrogeomorphic, biogeochemical, morphological) as well as social and economic criteria. The detailed data for the planning and designing of these wetlands are described in Comín et al. (2014). Simple restoration projects consisted of enlarging the area of the wetlands and facilitating water inflows and outflows to increase the residence time of the wetlands up to a minimum of 5 days except for during intense storm days.

The in-stream wetlands comprised 2–10 ha on both sides of a drainage stream with impervious clayed earth dikes constructed perpendicularly to the water flow for water retention. The water column in these wetlands ranged between 20–100 cm *Phragmites australis* (Cav.) Trin. ex Steud. was already present prior to the beginning of wetland construction in the central part of these wetlands and has progressively colonized all of the newly created wetland areas. The off-stream wetlands comprise 1–30 ha including long-abandoned agricultural fields flooded with water from drainage streams. The water column in these wetlands was smaller (e.g., 10–30 cm) and remained dry during periods of low water flow in the drainage streams. The water outflow was facilitated through small canals at the outflows of these wetlands. The plant cover in the off-stream wetlands consisted primarily of semi-aquatic species and was generally sparse (e.g., 10–20% of the total wetland area) compared to the in-stream wetlands (e.g., 50–90%) due to their permanently flood conditions, which were established by expanding the former drainage streams (width 50–100 cm; depth 20–50 cm) of agricultural irrigation return flows.

Water samples were collected bimonthly at the wetlands' inlets and outlets during 2012–2014 (i.e., 3 years following the completion of wetland construction). For some of these wetlands (7 in-stream and 2 off-stream), this sampling frequency was increased depending on the agricultural activities performed in the study area (e.g., irrigation, fertilization, soil maintenance works). In these cases, intensive samplings were conducted taking water samples during three consecutive weeks in order to obtain a more accurate idea of the NO_3^- patterns and the wetlands performance. Thus, during the study period, 17 samplings in non-irrigation season and 18 samplings in irrigation season were carried out. Water discharge rates were also measured at the time of sampling in the wetlands' inlets and outlets with a flow-meter. NO_3^- was analysed using standard methods (APHA, 2012).

2.2. Data treatment and statistical analysis

Significant differences ($p \leq 0.05$, $p \leq 0.01$) were evaluated by means of a one-way ANOVA test for normally distributed data. Data that could not be transformed to meet the normality and homoscedasticity assumptions required by the ANOVA test were analysed using the non-parametric Mann-Whitney *U* test. All analyses were conducted using R software (R Development Core Team (2011)). The wetland residence times (RT) were calculated with Eq. (1):

$$RT = V/Q \tag{1}$$

where Q is the average water inflow and outflow rate (m^3 d^{-1}), and V is the volume of the wetlands (m^3).

2.2.1. Kinetic model

Although Kadlec (2000) reported that the first-order plug-flow kinetic model was not effective (Kadlec and Knight, 1996), it is still the most appropriate method available to describe the removal