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Implications for constructed wetlands to mitigate nitrate and pesticide pollution in agricultural drained watersheds

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ABSTRACT

In the context of subsurface drainage, the mitigation of agricultural pollutants means intercepting water flows using green infrastructures such as constructed wetlands (CWs). First, based on a scientific review, this paper analyses how efficiently CWs can remove nitrate and pesticides from the runoff in drained agricultural watersheds. Average efficiency ranges from 20 to 90% and from 40 to 90% for pesticides and nitrate respectively. The main processes involved are based on microbiological activities, for which hydraulic residence time is a key factor. In order to successful implementation of such a wetland system, hydrological diagnosis of water flow and pollutant transfer at different watershed scales should be provided. Typically, the transport and transformation of pollutants shows clear seasonality depending on the application of nitrate (throughout the whole year) and pesticides (only after application periods).

We suggest two interception strategies based on field experiments. The "on-stream" strategy means the establishment of free water surface (FWS) CWs directly on streams/ditches and the interception of all drainage flows: a solution suitable for nitrate removal. The "off-stream" strategy requires the establishment of CWs outside of streams/ditches, whereas interception targets only the most polluted water flow, for instance during the period after pesticide application, requiring farmer's involvement.

Suggestions are also made for FWS CW design (a geotechnical survey, topography constraints, etc.) respecting ecological engineering concepts. A following size range is proposed: 76 m^3 per drained hectare, equivalent to 1% of the upstream area, given a maximum water depth of 0.8 m. Nevertheless, CWs must be considered as a complementary tool dedicated to transfer reduction, and as part of broader actions aimed at reducing pollutant loading at the plot scale.

1. Introduction

To respond to the requirements of the European Water Framework Directive (2000/60/CE) in terms of water pollution by agricultural non-point source pollution, actions can be implemented at different scales (European Union, 2000). Chemical inputs including fertilizers (nitrate; see Tanner and Kadlec, 2013) and pesticides (see Stehle et al., 2011; Vymazal and Březinová, 2015) are a source of this non-point source pollution. Reducing their use is the first essential stage in limiting the quantities of pesticides or nitrate reaching aquatic environments. For example, The French EcoPhyto Plan (Ministry of Agriculture, 2008) includes a 50% reduction in the quantities of pesticides applied for the next 10 years compared to 2008. However, given that fertilizers and pesticides continue to be applied, a portion will always be transferred toward aquatic environments. Complementary actions to the reduction of applications may also be necessary, including setting up buffer zones between the output of agricultural fields and the receptor environments to partially reduce pollutant flows (Correll, 2005; Reichenberger et al., 2007; Gregoire et al., 2009). Among these buffer zones, grass strips have been widely studied (CORPEN GZT, 2007). These impose an untreated zone between the field and the surface waters, thus reducing the quantities of pollutants reaching these waters (runoff, spray drift). Given their high infiltration capacity, grass strips can reduce pollutants from agricultural runoff (Lacas et al., 2005). However, their efficiency drops drastically when the soil gets saturated (limited infiltration) or when the flow to be treated is channelled and no longer diffuse through the grass strip (Souiller et al., 2002). Another case that limits the efficiency of grass strips is the management of waters coming from tile drainage. The hydrological functioning of tile drainage makes it possible to channel flows coming from the entire surface of an agricultural plot or a watershed to a single, easily identified point. Therefore, artificial wetlands (AWs)

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designed to improve the quality of water drained from agricultural land can be efficient and are easy to implement. Constructed or artificial wetlands are man-made wetlands designed to mimic the biofiltration action of natural wetland systems (Forbes et al., 2004; Vymazal, 2007). Thus in the application of ecological engineering concepts, the goal is to improve the natural function of natural wetlands in order to treat water pollution issues. The term "artificial wetlands" has no legal existence, and nor do the grass strips along water edges. However, it is its function that provides it with its "buffer" or retention role within the watershed. According to the classification proposed by Fonder and Headley (2010), different types of constructed (artificial) wetlands can be distinguished depending on their hydraulic function. They vary from subsurface flow systems (if the water course crosses a porous filter) to free water surface (FWS) systems, which can have shallow and deep sections and range from marshes (intermittent runoff) to lagoons (permanent runoff). For easier understanding and coherence with commonly used terminology, we will hereinafter use the term constructed wetlands (CWs). Since the FWS CWs are dominatingly used for treatment polluted runoff from agricultural watersheds, the further text considers this type of CWs.

The main objectives of the study are to: (1) analyse and synthesize results from literature and our earlier studies on the losses of nitrate and pesticides as well as their removal efficiency in FWS CWs purifying runoff from drained agricultural watersheds; (2) suggest polluted flow interception strategies and design parameters for FWS CWs based on field experiments.

2. Material and methods

2.1. Literature review

The first part of this paper details the pollution dissipation processes and the efficiency FWS CWs' treating polluted runoff from drained agricultural watersheds which are (1) reported in the international peer-reviewed literature, and (2) gathered in the previous field studies carried out by the *Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture* (IRSTEA), France. To find the literature sources via the Thomson-Reuters ISI Web of Science, the combination of keywords "artificial wetland(s)", constructed wetland(s)", "nitrate(s)", "pesticide(s)", and "tile-drain" or "drainage" have been used. In addition, the analysis is based on studies published by our research group and some other regional reports. The IRSTEA-based field studies have been carried since 2006 on various sizes of plots and watersheds in France (Tournebize et al., 2008, 2015a; Passeport et al., 2011). The specificity of drainage in terms of seasonality and transfer modality is presented in the second part of the paper. Finally, the part three introduces design and implementation aspects and shares experience from literature as well as IRSTEA-based field experiments.

2.2. Experimental sites description

Three experimental fields differing in scale were selected: a plot (46 ha, Indre et Loire, described in Passeport et al., 2013), a subbasin (355 ha, Seine et Marne, described in Tournebize et al., 2012), and a watershed (4000 ha, Seine-et-Marne, described in Blanchoud et al., 2013). These sites represent similar drainage conditions: average rainfall about 750 mm, hydromorphic soil (Gleyic Luvisol), crop rotation (mainly winter wheat, rape and barley), high proportion (>80%) of subsurface drainage system (perforated buried PVC pipe every 10 m space at 80 cm in deep due to more clayed layer below). For all three scales, water quality monitoring strategies were similar based on weekly flow weight sampling. All water samples were analyzed by the same laboratories; at IRSTEA for nitrate, and at CARSO (subcontractor) for pesticides, screening about 100 molecules, with average quantification limits of 0.01 μ/L).

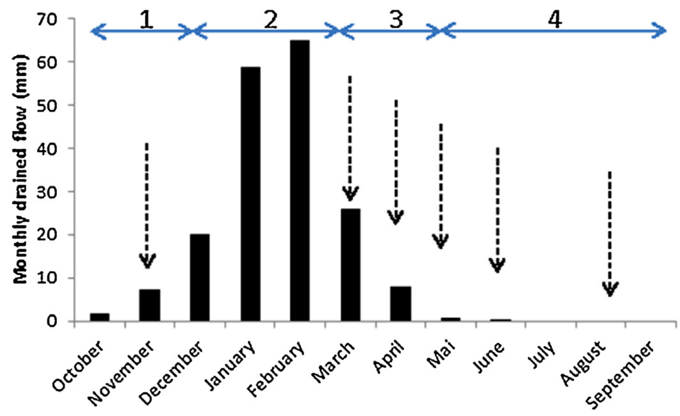

Fig. 1. Average monthly drainage flow (mm) according to the annual rainfall of 693 mm Periods: 1—initiation of drainage; 2—intense drainage season; 3—sporadic spring event; 4—no flow. Dashed arrows show the period of pesticide application for winter and spring cereal crops. Based on GIS ORACLE data from 1998 to 2012 (Tallec et al., 2015).

3. Dynamics of water and pollutant transfer in tile-drained agricultural watersheds

3.1. Hydrology

Knowledge of water pathways and flow at the watershed scale is needed in order to design and establish ecological engineering rules to optimize the purification function of CWs. Choosing to implement a CW requires prior analysis of the quantitative and qualitative dynamics of the waters drained at the output of the watershed.

The drainage runoff depends on the rainfall regime, and thus presents inter- and intra-annual variability. The interannual variability is explained by the alternating wet, dry and intermediate years, depending on the runoff precipitated each year. At the intra-annual scale, the behaviour of the drainage discharge at the watershed's outlet depends on events, presenting a chain of events between the peak discharges followed by a recession phase depending on the precipitation and the state of the soil's water holding capacity (Tournebize et al., 2008).

Over the entire hydrologic year, the drained watersheds in northwestern Europe are typically characterized by three different phases (Fig. 1) regardless of the climatic pattern of year (Tiemeyer et al., 2006; Borin and Tocchetto, 2007; Brown and van Beinum, 2009; Passeport et al., 2010).

The first step, called the "initial phase of drainage," generally appears at the beginning of winter; during this shallow/superficial groundwater recharge phase, rainfall mostly infiltrates, and very little rainfall is returned to the environment via drains. The second phase, called the "intense drainage season," generally during winter, is characterized by a very high restitution of rainfall. Since the soil is close to hydric saturation, any new water contributed as rainfall is restituted as outlet flow of the drain. Finally, the last phase (from spring to the beginning of fall) corresponds to the recession of superficial groundwater, with the soil becoming decreasingly saturated because of vegetation regrowth and the increase in evapotranspiration demand. For instance, in northern France, the annual mean drained runoff is approximately 180 mm (standard deviation 100 mm) which means very high volumes of water, depending on the size of the basin (Tournebize et al., 2004).