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A simple multi-criteria approach to delimitate nitrate attenuation zones in alluvial floodplains. Four cases in south-western Europe

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ABSTRACT

Four alluvial floodplains were selected in the European southwestern lowland area: the rivers Ebro, Bidasoa, Tagus (Spain) and the Garonne (France) were chosen. They have some common characteristics (alluvial aquifers, connectivity with the river, nitrate pollution) but differ in other important aspects (water table fluctuations, flooding dynamics, landscape control, land use, agricultural practices, climate). A comparative study considering nitrogen and carbon sources and the way they interact in the riparian zone was conducted in order to test a simple approach to delimitate permanent nitrate attenuation zones and to evidence the importance of site-specific attributes. The observation was based on a detailed monthly monitoring during a year ensuring data at high and low water periods. The tested approach results in a useful tool to spatially delimitate the attenuation zones. However, this approach is difficult to apply in areas where pollution sources are very diverse in type and in both time and space. This leads us to conclude that a general conceptual model cannot capture all the factors needed to understand the nitrate removal dynamics of a riparian zone. Hence, the study combines observation-conceptualization framework with river-riparian-upland connectivity and source-pathway-target continuity.

1. Introduction

Aquifers and rivers have traditionally been considered as independent compartments in the environment (Smith et al., 2009). Recent legislation, as the EU Water Framework Directive (WFD, 2000), emphasizes the need for an integrated management of river catchments, including better understanding of water exchange between aquifers (GW) and rivers (SW). These exchanges are usual in riparian zones where GW-SW interface may extend several hundreds of meters from the river, depending on the site-specific conditions. The surface-groundwater interface supports the purification of water by attenuating nitrates in the vegetation-soil system and in the aquifer (Sanchez-Perez et al., 1991a,b; Takatert et al., 1999). The riparian landscape is unique among environments because it is a terrestrial habitat strongly affecting and affected by aquatic environments (Mander et al., 2005). Its role has been highlighted as ecotone or as corridor, but in both the cases the riparian zones can act as conduits, filters or barriers controlling flows of energy, matter and species in landscapes (Burt et al., 2013). Some authors refer to them as Hyporheic Zone (Booker et al., 2008; Marmonier et al., 2012).

Often the riparian zone is taken to be synonym for floodplain, formed mainly of river sediments and often influenced by overbank flooding events, so that it connects upland and river through sur-

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face and subsurface hydrologic flow paths (Naiman et al., 2005; Burt et al., 2013). Intersecting these flow paths produces dynamic moisture and biogeochemical conditions in which processes impacting on the fate and transport of solutes can occur (Korom, 1992; Cirmo and McDonell, 1997; Gold et al., 2001; Vidon and Hill, 2004). As the moisture and biogeochemical conditions are heterogeneous in both space and time "hot spots" and "hot moments" concepts have been developed (McClain et al., 2003) to describe the function of riparian areas as buffer zones. The "hot" terms refer to a disproportionately high reaction rates relative to the surrounding area (spot) or to longer time periods (moment). Though the authors focused on N and C these concepts may also apply for a wide variety of constituents (Vidon et al., 2010).

Vidon et al. (2010) add a new step by distinguishing between transport-driven and biogeochemical process-driven hot spots and moments, which aims to highlight if the cause being behind the high reaction rate is a biogeochemical process or a transport event, although these phenomena should be considered simultaneously. As regarding denitrification, biogeochemically active hot spots in aquifers of the riparian zones are formed where flow paths with high concentrations of electron acceptor species (mainly oxygen, nitrate) intersect flows, or patches, with high concentration of organic carbon. Sources (point or non-point) and pathways (surface water or groundwater) of these elements are site-specific, and therefore vary from one riparian zone to another. The hydrological conditions at the river-groundwater interfaces have been shown to have a significant impact on denitrifying processes in aquifers (Lamontagne et al., 2005; Rassam et al., 2008). In riparian zones where groundwater levels are lower than soil root zones, denitrification has been found to attenuate nitrate efficiently in groundwater. In these conditions, the recharged river water, rich in organic matter, has stimulated the occurrence of denitrification (Sánchez-Pérez et al., 2003b; Iribar et al., 2008, 2015).

Agricultural activities are known to be a significant source of nitrate in groundwater. As alluvial plains, and mainly plateau areas feeding them, support intensive agricultural activities, they often suffer from groundwater nitrate pollution (Sánchez-Pérez et al., 2003a; Almasri and Kaluarachchi, 2007). As this pollution has become a significant environmental problem the ability of riparian buffers to remove agricultural contaminants has been studied extensively (McCarty et al., 2007; Rivett et al., 2008; Williams et al., 2014) and biological denitrification has been identified as a primary pathway for nitrate removal. Microbial "hot spots", with significant denitrification activity, have been found in patches of organic-rich soil and also at depths of several meters in zones near interfaces of different types of flows (McCarty et al., 2007). Among several factors controlling biological denitrification, hydrology and hydrogeology (Maître et al., 2003; Vidon and Hill, 2004; Lewandowski et al., 2009; Landon et al., 2011; Williams et al., 2014), geomorphology (Gold et al., 2001), geology and land use (Dosskey et al., 2010; Español et al., 2017), all of them as a continuum, can influence nitrate removal capacity of the riparian zones. Classifications based on these attributes have been proposed in order to fulfill requirements of the Water Framework Directive (Dahl et al., 2007).

The hillslope-riparian-river connectivity (McGlynn and McDonnell, 2003; Klaus et al., 2015) is widely acknowledged as a fundamental property of all ecosystems and has been taken as a primary element in conceptual model describing dynamics in riparian areas (Peyrard et al., 2008; Opperman et al., 2010). Lowrance et al. (1997) pointed out some of the most important multifunctional elements that riparian biotopes present (filtering pollutants, protecting riverbanks, regulating flows, improving microclimate, creating connectivity). Other authors (Opperman et al., 2010; Burt et al., 2013) emphasize floodplains as geomorphic features upon which ecosystems with immense ecological and economic value develop. According to this, efforts must be made to identify and manage hot spots for a better attenuation of pollutants by acting on disturbed riparian zones. In this way restoring hydrologic connectivity (Kondolf et al., 2006) or recovering forest areas to enhance biogeochemical processes (Burt et al., 2013; Comin et al., 2017) have been proposed. Booker et al. (2008) establish a typology of Hyporheic Zones based on their pollutant attenuation capacity and prioritize field data in order to determine the distribution and variability of environmental variables.

In this paper we are interested in the identification of hot spots in riparian zones. In fact, as pointed out by Vidon et al. (2010) "developing monitoring techniques to map the distribution of biogeochemical hot spots in riparian areas is likely to remain a particular concern in the future because other relevant fine-scale data that reflect physical and biological soil heterogeneity are not yet readily available". Our study has been carried out in the framework of the Attenagua Project. It is a research project INTERREG IVB SUDOE (Southwest Europe) funded by the European Regional Development Fund (ERDF). The main objective is to develop a method to identify the best locations for the use of the riparian area groundwater to supply drinking water. This involves taking advantage of self-purification capacity in riparian floodplains, namely denitrification. The method is based on the integration of the knowledge on physical-biogeochemical interactions in four alluvial riparian areas (lowland of the rivers Ebro, Bidasoa, Garonne and Tagus). These sites were chosen because of their differences in hydrology, landscape, land cover and anthropogenic context representative of the SUDOE region.

In the Attenagua Project nitrate attenuation activity in riparian areas was characterized by using different methodological approaches based on water physicochemical characterization (Bernard-Jannin et al., 2017), characterization of the invertebrate diversity and functionality (Español et al., 2017; Comin et al., 2017; Yao et al., 2017), characterization of the microalgae, analysis of denitrification potential, analysis of the bacterial community structure (Bodoque et al., 2017) and hydrobiochemical modeling (Sun et al., 2015). The present paper deals with the first approach mentioned, so that we take advantage of a high resolution dataset of physicochemical parameters to understand nitrates dynamics in relationship with water fluxes and carbon organic availability.

Based on the results obtained in the study sites, an approach is proposed to map the areas of natural attenuation, depending on the hydrogeological and landscape characteristics and sources of contamination. This paper does not aim to provide accurate spatial representations of the attenuation processes but to provide a good estimation of the attenuation zones (hot spots) with a simple method based on relative few field data. Furthermore this knowledge is essential to focus on the issues to be investigated in detail in site-specific research. Specific objectives are: i) To test a simple approach to delimitate permanent attenuation zones in riparian areas as regards nitrate pollution. ii) To put in evidence the importance that site-specific attributes have on these spots. This study combines observation-conceptualization framework with river-riparian-upland connectivity and source-pathway-target continuity.

2. Materials and methods

2.1. Study sites description

Four river meanders (Fig. 1) located in South-western Europe were selected: the rivers Ebro, Bidasoa, Garonne and Tagus. All of them are characterized by a combination of agricultural occupation and patches of natural riparian forest that might favour the potential degradation of agricultural pollutants. In order to favour the comparison of the study sites (Figs. 2 and 3) a wide variation of cli-