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Research Paper

Runoff, nutrients, sediment and salt yields in an irrigated watershed in southern Navarre (Spain)

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ABSTRACT

The environmental impact of irrigated agriculture on water quality was assessed in Landazuria watershed (Navarre, northeast Spain), a 479.5 ha watershed with 53% of irrigated agricultural land. In the framework of a long-term monitoring program, precipitation and discharge were measured at 10-min intervals and compound daily water samples were collected during the agricultural years (September to August) 2007–2016, and analysed for nitrate (NO_3^-), phosphate (PO_4^{3-}), sediment and total dissolved solids (TDS) concentrations. Typical agricultural management (including crop surfaces, irrigation and fertilization rates) was obtained from inquiries to farmers. Concentration and yield of the studied variables presented a high degree of variation, both intra- and inter-annual. Median concentration for the entire study period were 185, <0.05, 31 and 2284 mg L^{-1} for NO_3^-, PO_4^{3-}, sediment and TDS, respectively. NO_3^--N and PO_4^{3-}-P yields averaged 74 and 0.04 kg ha^{-1} $year^{-1}$, respectively. NO_3^--N yield was higher than in other agricultural land uses in Navarre and in the order of magnitude of other irrigated areas in the Middle Ebro Valley. PO_4^{3-}-P yield was in the same order of magnitude than in rainfed watersheds in Navarre but lower than in intensively grazed watersheds. Sediment yield was extremely variable, averaging 360 kg ha^{-1} $year^{-1}$, with 44% of the total measured load recorded in a few days. It was in the lower range of those measured in Navarre for rainfed agriculture and similar to those estimated in other irrigated areas of the Middle Ebro River. TDS concentration presented a significant decreasing trend since available salts were being washed out, while TDS yield averaged 1.8 Mg ha^{-1} $year^{-1}$. Long-term monitoring of irrigated areas is required to understand pollution processes in these agroecosystems and to adequately characterize the environmental impact of current agricultural practices on water quality, in order to implement, and adequately assess, measures to reduce agricultural pollution.

1. Introduction

More than 1.5 billion ha (about 12% of the world's land area) are used for crop production. Rainfed agriculture is the predominant agricultural production system, but increasing climate variability is bringing greater uncertainty in the production levels. Current productivity in rainfed systems is, on average, little more than half of its potential (FAO, 2013). However, agricultural production has grown between 2 and 4% per year over the last 50 years, while the cultivated area has grown by only 1% annually. More than 40% of the increase in food production has come from irrigated areas.

Irrigation has many advantages over rainfed agriculture, such as increased productivity, higher diversity of crops, more reliable harvests, or regional economic security (e.g., Duncan et al., 2008). For these reasons, a global increase in irrigated surface has been observed, especially in developing countries, where it doubled between 1962 and 1998 (FAO, 2003a). In Spain, the increase of irrigated area has been moderate but significant, with 7% more irrigated land between 1990 and 2009 according to the Spanish Ministry of Agriculture and Fisheries, Food and Environment (MAPAMA, 2017). In fact, irrigated agriculture has been a key factor in the agrarian Spanish system as it provides more than 50% of the final agrarian production with only 13% of the surface. Accord-

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ing to official estimates, in Spain an irrigated hectare produces, on average, six times more than a rainfed hectare, and generates four times more income. In Navarre (10,391 km^2, northern Spain), irrigated surface has increased in recent years to over 110,000 ha (approximately 25% growth between 2000 and 2015; DDRMAAL, 2017), being pressurized districts those implemented in the new irrigated land.

There is no question about the value of irrigated agriculture but there is an increasing trend to make it accountable for its impacts on the environment (e.g., Stockle, 2001). Agricultural land use is regarded as the main source of diffuse pollution (Novotny, 1999), and it has a wide range of associated environmental impacts such as changes in landscapes and plant and animal communities, and the deterioration of soil, water and air quality (Stoate et al., 2001; Merrington et al., 2002). Specifically, irrigated agriculture imposes severe pressure on the environment, as it accounts for the consumption of 70% of global water resources (FAO, 2003b), being the main reason behind the construction of most dams or aquifers overexploitation. Apart from the effects on the withdrawal water body, irrigation return flows can also cause hydrological changes in the receiving ones. Specific environmental problems in waters downstream of the irrigated areas are related, among others, to nutrients, sediments or salts.

Nitrate pollution is a major concern in irrigated areas since high nitrate concentrations have long been regarded as a threat for human health and ecosystems (e.g., Sutton et al., 2011). Despite the fact that nitrate leaching varies considerably with climatic conditions (e.g., Elmi et al., 2004), the actual impact of N pollution depends on specific features of the area such as the soil types (Kyllmar et al., 2014), the presence of reducing conditions in aquifers (Rivett et al., 2008) and the irrigation/fertilization management (Quemada et al., 2013). On the other hand, the mobility of phosphorus is rather limited, especially in arid or semi-arid regions (Brady and Weil, 2008). In these soils, only a small fraction of P is in soluble reactive form (phosphate) and can be incorporated into plants. For this reason, P losses are normally related to soil or sediment losses (Edwards and Withers, 2008). As a consequence, P pollution is greatly conditioned by erosion, especially in arid and semi-arid areas.

Erosion processes in agricultural land tend to be significantly higher than in other land uses (García-Ruiz et al., 2015). Erosion removes preferentially the fine fraction of soils, which is enriched in nutrients and organic matter (Merrington et al., 2002). Soil erosion rates are extremely variable (García-Ruiz et al., 2015) and depend on both natural factors (climate, slope, soils, bedrock...) and agronomic management (cover, tillage...). Finally, the leaching of salts is a requirement of irrigated agriculture (Letey et al., 2011) since its build-up in soils can be deleterious for plants, decrease productivity and even force the abandonment of cultivation. However, leached salts will reach water bodies downstream, affecting its quality for human consumption or ecosystem uses (Nielsen et al., 2003). The amount of salts leached depends on different factors such as climate, hydrogeological conditions or irrigation management (Merchán et al., 2015c).

In Navarre, the environmental impact of agriculture is investigated in a network of experimental watersheds (Fig. 1) implemented by the former *Department of Agriculture, Livestock and Food* of the Government of Navarre. This network includes representative agricultural land-uses in the region (et al., 2008, 2010; et al., 2008, 2010). An irrigated watershed (Landazuria) was included in the monitoring network in 2006. The climatic, geologic and agronomic characteristics of this watershed make it representative of the recent pressurized irrigated areas in the Middle Ebro Valley, with over 900,000 ha dedicated to irrigated agriculture, and approximately half of this surface being pressurized irrigation systems (CHE, 2017). In addition, in the framework of the project LIFE-Nitrates (LIFE + 10 ENV/ES/478), a consortium of public institutions constituted by the Government of Navarre (GN), Environmental Management of Navarre (GAN), Navarre Institute of Agricultural and Food Technologies and Infrastructures (INTIA) and CRANA Foundation conducted a detailed study on the "Impacts of agricultural practices on nitrate pollution of continental waters" (www.life-nitratos.eu/). One of the study sites investigated in this project was the irrigated watershed monitored by the Government of Navarre.

In this paper we present the data obtained during the agricultural years 2007–2016 in the irrigated watershed (Landazuria). Given the high variability in climatic and agronomic conditions in specific study cases and the different processes affecting different pollutants, the analysis of detailed and long-term temporal series of a wide set of variables is paramount to better understand the pollution of water bodies as a consequence of agricultural land use, particularly in irrigated areas. The main objectives were: (1) to estimate the effects of irrigated agriculture on water quality, specifically in terms of nitrate, phosphate, sediment and salts concentration in the watershed outlet and exported yields; (2) to determine the controlling factors explaining that behaviour; and (3) to contextualize the obtained estimations and inferred controlling factors with those reported in other irrigated and rainfed watersheds, paying especial attention to the difference between them.

2. Methods

2.1. Experimental watershed

Landazuria watershed covers an area of 479.5 ha and is located in southern Navarre (Fig. 1). It is relatively flat, with slopes between 3.5 and 5%. A single 1st order stream drains the watershed. The geographical coordinates of the watershed outlet are 42°15′3.5″N and 1°35′3.4″W. According to data collected for the period 1992–2016 around 5 km south (meteorological station Bardenas-El Yugo, Government of Navarra) the climate in the study zone is Dry Mediterranean. Average annual temperature is 14 °C, but it can reach values as low as −8 °C in winter and as high as 41 °C in summer. Annual precipitation is 426 ± 114 mm (average ± standard deviation) whereas annual reference evapotranspiration (FAO Penman-Monteith, Allen et al., 1998) is 1369 ± 101 mm, i.e., more than three times higher and much less variable.

The geology in Landazuria is represented by Tertiary and Quaternary materials. The Tertiary materials appear as a bottom layer several hundred metres thick, composed of alternating gypsum, and red clays, with occasional intercalations of fine (centimetres to decimetres) limestone layers (DOPTC, 2003a, 2003b). The Quaternary materials cover in most of the watershed surface the Tertiary materials, and they are composed mainly by detrital sediments, gravels with some limestone clasts, alternating with sands, silt and clays (glacis) of Pleistocene-Holocene age. The synclinal structure and extremely low hydraulic conductivity of the Tertiary materials (<10^{-8} m s^{-1}; DOPTC, 2003a, 2003b) avoids deep percolation of water within the watershed.

According to a detailed survey including 78 direct observations (Government of Navarre, 2005), soils developed in Landazuria present mainly clay loam or silt loam textures and are deep, with the exception of eroded hills (Fig. 1c). The most common series correspond to Typic Haplustepts and Typic Calciustolls, although other series do appear. Organic matter content ranged between 1.7 and 2.7% while pH ranged between 8.1 and 8.9. Landazuria soils presented in general low salinity, with some slight to moderate salinity level in the valley bottoms and in soils developed over Tertiary marls.