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Seasonal and land use impacts on the nitrate budget and export of a mesoscale catchment in Southern Portugal

Mariela A. Yevenes*, Chris M. Mannaerts

Department of Water Resources, Faculty of Geo-Information Science & Earth Observation, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

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ABSTRACT

Stream nitrate nitrogen exports are an important indicator of agricultural impacts on aquatic health in catchments. Quantitative assessment of factors and processes affecting stream nitrate loadings is complex because of the large number of causal factors and processes, such as weather and rainfall, catchment hydrological behavior, soils, land use practices and biogeochemical processes. An eco-hydrological catchment modeling approach, using the SWAT model driven by detailed field data, was used to analyze the nitrate export and the components of the nitrogen budget of the 352 km^2 upper Roxo river catchment in Southern Portugal. A detailed eight-year record (2001–2008) of the monitoring of weather, reservoir inflow, stream biogeochemistry, soils, in-stream and groundwater quality, and fertilizer application was used to calibrate and validate the streamflow and nitrate loadings obtained by the model. Results indicated a strong seasonal variation in nitrate exports, closely related to temperature and rainfall. Monthly nitrate loadings varied from 0.02 to 2.48 $kg\,N\,ha^{-1}$ during summer and between 0.03 and 14 $kg\,N\,ha^{-1}$ during late autumn and winter. Stream nitrate values, ranging from 1.5 to 16.5 $mg\,N\,L^{-1}$, were strongly related to extreme rainfall occurrences and wet periods. Detailed analysis of nitrate budget components at the sub-catchment level enabled evaluation of the impacts of the various processes affecting the nitrate nitrogen pool of the catchment. Besides high fertilizer inputs for annual crops, it was shown that biological nitrogen fixation and wet deposition by rainfall should be accounted for in input balances. Where denitrification naturally reduces nitrate levels in soils, streams and the reservoir, the largest contribution to stream nitrate originates from leached soil nitrate reappearing in groundwater baseflow, compared with less than 2% from direct surface runoff during high rainfall events. A fertilizer reduction scenario was effectively implemented to evaluate remedial nitrate control policies in accordance with the European Nitrate and Water Framework Directives. Agricultural practices and seasonal weather fluctuations were the main reasons for temporal variations in nitrate export via small streams to the main reservoir.

1. Introduction

Nitrogen levels in streamflow are important indicators of environmental catchment conditions (Piatek et al., 2009; Mulholland et al., 2005; Arheimer and Brandt, 1998). A multitude of human activities, such as agricultural practices or urban residual waste water effluent releases, may produce an excess of nitrogen supply in a catchment, and can lead to increased nitrogen losses, especially in the form of nitrate nitrogen (nitrate), thus disturbing and impacting the water quality of ecosystems (Ventura et al., 2008). Concern about nitrate impacts on freshwater bodies from activities such as agriculture dates back more than 40 years ago, when the Commission of the European Community (CEC) became interested in maximizing the fertilizer potential of animal slurry applied to agricultural areas (Sluijsmans, 1978). Nowadays, it is still a concern in the European Water Framework Directive, whereby several agriculture-dominated regions across Europe have been classified in the European Nitrate Directive 91/676/CEE as areas vulnerable to nitrate contamination from agricultural sources.

The Roxo river is an upper tributary of the Sado basin and is located in the important agricultural Alentejo region of Southern Portugal. The catchment area is within the zone of influence of the large Alqueva dam and reservoir, and has been classified as a vulnerable zone since 2006 according to the European Nitrate Directive 91/676/CEE. The Roxo upper catchment (352 km^2) drains into a reservoir, which is the main source of the domestic water supply for Beja city, as well as the water supply for the local mining industry and some important irrigation areas (ABROXO, 2009). The reservoir has, however, been under considerable water stress for several years owing to the combination of interannual weather variability that affects natural rainfall supply, increased water consumption, and contamination threats of varying origin

* Corresponding author. Tel.: +31 053 4874474; fax: +31 053 4874336.
E-mail address: yevenesburgos@itc.nl (M.A. Yevenes).

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(UNEP, 1997). There is serious concern among the local and regional authorities regarding the Roxo reservoir, related to both water quantity and quality.

Several field studies and data from the Roxo catchment have indicated high nitrate concentrations, around 15 mg N L^{-1} in small streams and shallow groundwater (Vithanage, 2009; Gurung, 2005; Chisha, 2003). Gurung (2005) suggested that the Roxo reservoir is a hypertrophic system, because maximum nitrate concentrations of 14 mg N L^{-1} and high values for other eutrophication indicators such as phosphorus and chlorophyll-a were regularly observed in the reservoir. Vithanage (2009) recorded NO_3^- levels ranging from 2 to 13 mg N L^{-1} in streams located in the southern part of the catchment, which in fact significantly exceeds the nitrate levels (5.65 mg N L^{-1}) established by the European Water Framework Directive (2000/60/EC). However, it is known that only a small percentage of the net nitrogen pool in a catchment is generally exported to streams (Boyer et al., 2002), while the rest is retained or lost in the watershed system through denitrification or volatilization into the atmosphere before reaching the water body (Filoso et al., 2003). Nevertheless, nitrate export studies remain important because excess nitrogen inputs in a water body can dramatically increase primary productivity and decrease the water quality of the impoundment (Alvarez-Cobelas et al., 2008; Caraco and Cole, 2001). Observation of high nitrate concentrations in natural waters may also be indicative of the possible presence and flows of other nutrients (e.g. phosphorus) or contaminants (e.g. pesticides).

Several studies consider an observation period of five years or more as sufficient for nitrate export studies, since this enables the spatial and temporal variability involved in the seasonal periodicity of nitrogen fluxes to be captured (Alvarez-Cobelas et al., 2008). Local medium-term studies have proved to be better than single-year analyses when it comes to understanding the controlling factors of catchment nitrogen fluxes (Alvarez-Cobelas et al., 2008; Schilling and Zhang, 2004).

The nitrate export of a catchment is affected by environmental factors such as ambient temperature, rainfall, runoff, streamflow, soils and land use, including agricultural practices such as fertilizer application and potential point sources (Schilling and Zhang, 2004). Catchment studies carried out in Europe have reported nitrate export values ranging from 0.4 kg N ha^{-1} to 17 kg N ha^{-1} yr^{-1} (Alvarez-Cobelas et al., 2008; Isidoro et al., 2006). With regard to the Roxo catchment in particular, mineral fertilizer, manure and residual waste water disposal are potentially major non-point sources of excess nitrogen.

The aim of this study is to estimate the nitrate exports by streamflow from the small streams to a water reservoir in the Roxo catchment in Southern Portugal, in order to assess the relative importance of environmental factors such as rainfall distribution, streamflow, land use and agricultural practices affecting nitrate loadings and losses in a mesoscale catchment, and ultimately to predict the hydrological or biogeochemical processes controlling the stream nitrate dynamics. The Soil and Water Assessment Tool or SWAT 2005 eco-hydrological model (Neitsch et al., 2005, 2002) was used for this purpose, using an eight-year period (2001–2008) of monitoring data. The SWAT model has been extensively used to determine rainfall-runoff responses and nutrient loadings in streamflow and biogeochemical processes in moderately and poorly gauged catchments (Lam et al., 2009; Hu et al., 2007; Pohlert et al., 2005).

2. Materials and methods

2.1. Study area

The study area is located in the Roxo catchment in the Beja district of Alentejo province, Southern Portugal (37°46′44″N to 38°02′39″N latitude and 7°5′47″E to 8°12′24″E longitude; Fig. 1). With a catchment area of 352 km^2, it is considered a mesoscale catchment. The topography varies from nearly flat to gently sloping terrain, with elevations ranging from 123 m at the catchment reservoir outlet to 280 m.a.s.l. near Beja city.

Alentejo province alone yields 75% of Portugal's total wheat production (Paralta and Oliveira, 2005). The region and the Roxo catchment are dominated by agricultural activities. The major crops produced in the region are winter wheat, maize, alfalfa and sunflower as rotation crops, and olives, vineyards (grapes) and cork oak as perennial agricultural crops (Table 1). Agricultural land covers more than 80% of the catchment. Winter wheat and alfalfa, as intensive crops, commonly require around 100 kg N ha^{-1} yr^{-1} of fertilizer, whereas recommended nitrogen fertilization for maize is around 150–200 kg N ha^{-1} yr^{-1} (Paralta and Oliveira, 2005; personal communication M. Varela of Centro Operativo e de Tecnologia de Regadio (COTR) and R. Nobre of Escola Agraria do Beja, Portugal). For olive and oak plantations, fertilizer application and amounts are quite variable, and depend mainly on foliar analysis and tree age. However, an average application of 100 kg N ha^{-1} yr^{-1} is common practice for olive orchards in the production season (personal communication M. Varela of COTR). Fertilization of range and grassland is negligible and is an uncommon practice in Portugal. Some areas of natural forest and silvicultural activities are present in the south of the catchment. Literature related to fertilizer use in eucalyptus plantations indicates minimal use: about 60 kg N ha^{-1} applied at the start of the plantations (Filoso et al., 2003). Two other natural nitrogen input sources in the catchment are biological nitrogen fixation by crops such as alfalfa, and atmospheric wet deposition by rainfall.

Water in the catchment drains into an artificial impoundment, the Roxo reservoir (maximum volume approximately 10^8 m^3), which was built in the early sixties and is used for municipal water supply to Beja city and its approximately 161,000 inhabitants, for the local mining industry, and for irrigation water supply to several areas (ABROXO, 2009). The irrigation water volume accumulated in Roxo reservoir is not used within the catchment, but is used to irrigate areas downstream of the reservoir. Water for crop irrigation in the catchment area comes from shallow groundwater, which is pumped to center pivot systems to irrigate crops such as alfalfa and maize (Table 1). The sewage waters from Beja city are channeled to a waste water treatment plant, before the residual waters are released into the Chamine-Pisoes streams in the upper part of the catchment. This also yields an additional and relatively constant nitrogen input and loading in the upper catchment stream network. The reservoir lake and riparian area cover an average area of 11.9 and 20 km^2, respectively, and represent 3.38 4% and 10.2% of the total catchment area.

The long-term mean annual rainfall in the catchment region ranges from 500 to 550 mm. Soil survey using the FAO-UNESCO classification system identified four main soil types in the catchment: Luvisols, Litosols, Planosols and Vertisols (Sen and Gieske, 2005). The Luvisols cover 64% of the study area and are consequently the dominant soil type (Gamises, 2009). This soil type, with loam to clay loam texture, extends from the northeastern part to the southern part. Soil physical properties include texture, bulk density, available water capacity, saturated conductivity and organic carbon percentage (Table 2). We used measured soil properties at our own institution (Gamises, 2009; Gokmen, 2006) in combination with official Portuguese soil data and information (Cardoso, 1965).

2.2. Data collection and nitrate export prediction

For this study, water quality data and information on nitrogen were collected from various sources. Groundwater nitrate (Paralta