Chapter 2

Modelling the Contribution of Land Use to Nitrate Yield from a Rural Catchment

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Abstract

The nutrient flow dynamics in rural landscapes are among the basic characteristics of landscape functioning. In this study, the ecohydrological model SWAT (Soil and Water Assessment Tool) was applied in a small rural catchment in northwest (NW) Spain to evaluate the contribution of land use on nitrate losses and to assess the relative importance of different pathways by which nitrate is delivered to the drainage network. The model was first calibrated and validated at a monthly time step. The SWAT model performance was satisfactory ($R^2 > 0.5$; Nash-Sutcliffe efficiency (NSE) > 0.5 and percent bias (PBIAS) < 10%) during both the calibration and validation periods, indicating that SWAT predicted the nitrate discharge accurately. Using the calibrated SWAT model, this study showed that agricultural lands, even though they represent only 30% of the catchment, were main contributor to the nitrate losses accounting for about 77% of the total nitrate yield. The model results also indicated that, irrespective of the land use, groundwater flow is the main pathway for nitrate losses (63%); therefore, appropriate management practices aimed at decreasing nitrate leaching will be key factors in reducing nitrate yield in the study catchment.

Keywords: nitrate yield, rural landscape, modelling approach, land use, NW Spain

1. Introduction

The nutrient flow dynamics in rural landscapes are among the basic characteristics of landscape functioning [1]. Nutrient cycling has been well documented in this type of catchment, and a great deal of research has focused on analysing the impact of human activity on nutrient losses [2–4], identifying agricultural activities as the primary source of diffuse pollution of water resources [4, 5]. One of the major diffuse pollutants that is sourced from agriculture is nitrate (NO_3-N), which, due to its high solubility, is easily leached from the soil to both ground and surface waters. In fact, nitrogen leaching from agricultural land has become a common problem in many European regions [6]. An example is Galicia (NW Spain), which has been identified as a European region of high soil and water eutrophication risk [7]. In fact, in less than 10 years, an increase in nitrate concentrations from 2–3 to 10–20 mg l^{-1} was detected in many rural areas [2].

The Water Framework Directive (WFD) demands the implementation of measures in order to improve water quality, the ultimate WFD target being that all waters in the European Union should be in good ecological condition by the end of 2015 [8]. This requires knowledge of the effects of natural conditions and land uses on diffuse pollutant losses at catchment scale and to understand the pathways transporting these pollutant losses from land to water bodies. Different approaches have been adopted to address these issues and the control of diffuse pollutants at source (e.g., through efficient land management practices) is often seen as the optimal solution to potential problems. However, conducting field experiments to better understand diffuse-source pollution and design appropriate management solutions is expensive, time consuming and spatially impractical at catchment scale [9]. In this context, simulation models have become useful tools to evaluate water quality under current conditions and investigate the consequences of land use, management and climate change on water quality. Therefore, they would be helpful to find appropriate measures for assessing environmental and ecological status, taking into account factors such as climate, land and water use, with these becoming vital tools in catchment management. However, before any process-based catchment model can be applied, the performance and reliability of the model must be tested with measured data otherwise model simulations may lead to erroneous results and to faulty design of protection measures. A large number of hydrological models, such as AGNPS (Agricultural Non-point Source Pollution Model), ANSWER (Areal Non-point Source Watershed Environment Response Simulation) and SWAT (Soil and Water Assessment Tool), have been applied to assess these issues. The SWAT [10, 11] is one of the few physically based approaches describing processes responsible for the transfer of nutrients from soil to water with an explicit representation of plant growth and impact of agricultural management practices. It has been a widely used and scientifically accepted tool for modelling diffuse emission of nutrients and water quality in rural areas, mainly in large catchments [12]. Therefore, there is still a paucity of SWAT research on predicting nutrient discharge in small catchments.

In this context, this research provides the results of a study of nitrate losses from the Corbeira catchment, which drains a small (16 km^2) rural landscape in Galicia, NW Spain. The specific objectives of the research were to (i) evaluate the performance and capacity of the eco-hydrological SWAT model to predict nitrate discharge in the Corbeira catchment at monthly time step, (ii) determine the contribution of land use on nitrate losses from this catchment and (iii) assess the relative importance of different pathways by which nitrate is delivered to the drainage network.

The Corbeira catchment was selected because it is representative of the rural landscape in NW Spain, characterized by a distinctly mixed use of the territory, divided between cultivation, pasture and forest. In addition, it is located upstream of the Cecebre reservoir, which is the main water supply for the city of A Coruña and surrounding municipalities (450,000 inhabitants) in northwest Spain. Moreover, this reservoir was declared a Special Area of Conservation and Site of Community Importance included in the Natura 2000 Network. Also, a large number of measurements and analyses related to diffuse pollution have been conducted in this catchment since 2004, which reduces model uncertainty.

2. Material and methods

2.1. Study area and data

The study area was the Corbeira catchment, a small catchment (16 km^2) located at about 30 km northwest of the city of A Coruña (Galicia, NW Spain; **Figure 1**), at a latitude of 43° 13′2.3″N and a longitude of 8° 13′43.9″W. The elevation in the catchment ranges from 47 m at the outlet of the catchment to 470 m at the highest peaks. The topography is moderately steep with an average slope of 19%, and on some areas of the catchment, the slope gradient can reach more than 55%. The geology of the drainage is homogeneous and is dominated by basic schists of the Órdenes Complex [13]. The main types of soil are Umbrisols and Cambisols [14] with great depth and silt and silt-loam texture. The distribution of land cover in the study area is as follows: 65% forest (mainly commercial eucalyptus plantations), 26% pastures and 4% croplands (maize and winter cereal), with the remaining land occupied by impervious areas

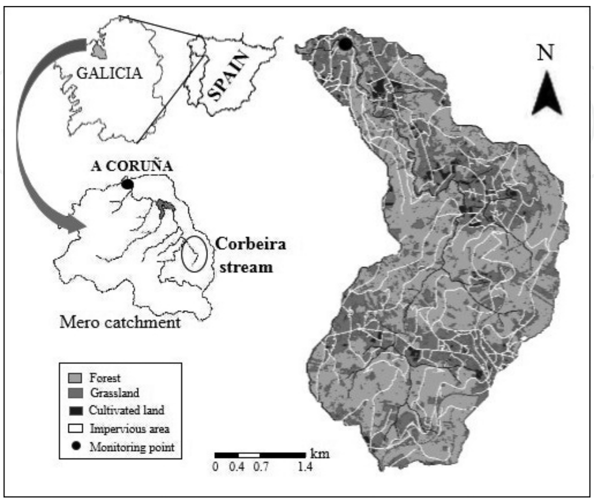

Figure 1. Location of the study area and land use distribution in the Corbeira catchment.

(built-up and infrastructure) mainly distributed in the agricultural zone. Organic and inorganic fertilizers are commonly applied to the agricultural area throughout the year, including the wettest months. However, forest areas are not fertilized. The annual N input to the catchment is approximately 37.8 kg N ha^{-1}, 49% comes from organic fertilizers, 16% from inorganic fertilizers, 2% from population centres and the remaining 33% of atmospheric deposition [15, 16].

The prevailing climate in the study area is humid temperate. The mean annual rainfall is about 1050 mm (historic series: 1983–2009), distributed evenly throughout the year. The mean temperature is 13°C, and the mean annual discharge is around 0.20 m^3 s^{-1} [17].

2.2. SWAT model description

The eco-hydrological SWAT model is a process-based, spatially semi-distributed and continuous model that operates at daily intervals [10]. It was developed by the Agricultural Research Service of the United States Department of Agriculture (USDA) to quantify and predict the impact of agricultural management practices on water, sediment and chemical yields in large complex catchments [10, 11].

In the model, the watershed is divided into sub-basins connected by a stream network. Each sub-basin, in turn, is separated into Hydrological Response Units (HRUs), i.e., territorial units characterized by a specific combination of land use, soil type and slope. The model considers each HRU to be homogeneous in terms of vegetation growth, processes of generation of runoff, erosion and nutrient loading, so they are useful to discriminate the main water, sediment and nutrient sources within each sub-basin. SWAT simulates each HRU separately and the results from HRU_S are integrated at sub-basin scale. It is assumed that there is no interaction between HRUs. The model is flexible in the discretization of the watershed, allowing the user to choose the outlet of the sub-basin. This makes it possible to obtain results of water quantity and quality for any previously selected point, which usually coincides with monitoring stations.

SWAT model simulations are divided into two parts. The first part (land phase) is related to the amount of water, sediment and nutrients delivery from each HRU to the main channel in each sub-basin. The second part (water phase) is related to the behaviour of water and other elements through the channel to the catchment outlet. The model simulates the nitrogen cycle in soil and groundwater, taking into account denitrification, nitrification, mineralization, volatization and plan uptake. SWAT distinguishes five different pools of nitrogen in the soil: two pools are inorganic forms of N and the other three are organic forms of nitrogen. Nitrate is transported from upland areas to stream network via surface runoff, lateral flow and groundwater flow. The amount of nitrate transported by water is calculated by multiplying the nitrate concentration in the mobile water by the volume of water moving in each pathway. Additional informational about the SWAT model can be found in [11].

2.3. SWAT model set-up and input data

The ArcSWAT version 2009.93.7b was used to create the input files for SWAT. The input data and the sources used to create the SWAT model setup of the Corbeira catchment are summarized in **Table 1**. The catchment outlet was set at the Corbeira catchment gauging station, where the hydrological and water quality data are measured. The DEM was used to delimit the catchment, delineate the stream network in the study area and to obtain the topographic parameters, such as slope gradient and slope length; and stream network characteristics, such as channel slope, length and width. Slope, soil and land use data were used for model parameterization, resulting in 12 HRUs. Slope was divided into three classes (0–13%, 13–25% and >25%) following the FAO classification. Seven soil types were identified according to IUSS Working Group WRB [14] classification. The major land uses were defined as 65% forest, 26% pasture, 4% croplands and 5% impervious. The land use pasture and cropland (maize) were parameterized based on the SWAT land use classes, using the SWAT plant codes *meadow bromegrass* and *corn* to represent pasture and maize land covers, respectively, while a new land use was created for the eucalyptus forest area, based on literature [18, 19]. Several management operations (e.g., planting, harvesting and fertilization) were applied for maize and pastures based on knowledge of crop management practice in the catchment and on interviews with the farmers in the catchment.

Data type	Data description	Source
Topography	Digital Elevation Model (DEM), resolution (7 m × 7 m)	Xunta of Galicia
Soils	Soil types (1:50,000)	Xunta of Galicia
Land use	Land use classification	Landsat satellite images provided by Xunta de Galicia
Climate	Daily rainfall, maximum and minimum temperatures, relative humidity, solar radiation and wind speed	Galicia Meteorological Service

Table 1. Model input data sources for the Corbeira catchment.

2.4. Data used for calibration and validation

SWAT was calibrated and validated against nitrate load data measured at the catchment outlet. Nitrate load was calculated as the sum of the product of the mean concentration of adjacent samples by the cumulative flow for each interval of time between both samples. Stream discharge was calculated based on water levels recorded at a 10-min frequency and the level-discharge rating curve and was summarized into mean daily discharge. Water samples for nitrate determination were collected manually with sampling intervals of 10 and 15 days and more intensively (2–8 h) during runoff events, for which an automatic sampler (ISCO 6712) was used, with storage capacity for 24 one-litre polyethylene bottles. The sampler was programmed to begin sampling with increases of 2–3 cm above the stream water level at the beginning of each rainfall event. Nitrate concentrations were analysed by capillary electrophoresis. Model calibration was performed manually on a monthly time step to obtain a reasonably good agreement between the observed and simulated values. The simulation period was limited to five hydrological years (2005/2006–2009/2010) because of data availability; the first three years (2005/2006–2007/2008) were used for calibration and the last two

(2008/2009–2009/2010) for validation. Prior to calibration, the model was warmed up (March 2001–October 2005) to minimize the effect of uncertain initial conditions.

2.5. Model performance evaluation

The model performance was evaluated using the following statistical indices: determination coefficient (R^2), the percent bias (PBIAS) and the Nash-Sutcliffe efficiency (NSE). Information on the statistical equations and the goodness fit of a model at a different time step can be found in [20]. The recommended values for attaining a good model performance for nutrient yield simulations at a monthly time step are PBIAS between ±15 and ±30% and NSE between 0.50 and 0.60.

3. Results and discussion

3.1. SWAT model performance for nitrate yield estimation at catchment scale

The SWAT model used in this research was satisfactorily applied for simulating stream discharge in the catchment under study [21]. In this study, only the parameters that significantly affected nitrate loads such as nitrogen percolation coefficient (NPERCO), humus mineralization (CMN) and residue mineralization (RSDCO) were manually adjusted to provide a good fit between measured and simulated NO_3-N loads. **Table 2** shows the model results based on the performance indicators included in the study, whereas **Figure 2** illustrates the comparison between the measured and simulated monthly nitrate load at the catchment outlet. The simulated mean monthly values were close to the observed values during both the calibration and validation periods, with PBIAS within the 6% of measured NO_3-N load. In general, model simulations can be considered satisfactory ($R^2 > 0.5$; NSE > 0.5) according to the criteria given by Moriasi et al. [20], indicating that it is a valid tool to identify crucial pollution areas within the catchment.

	R^2	PBIAS	NSE
Calibration period	0.52	3	0.50
Validation period	0.54	6	0.53

R^2: regression coefficient, PBIAS: percentage of bias; NSE: Nash-Sutcliffe efficiency

Table 2. Calibration and validation statistics for monthly nitrate yield.

Although simulated NO_3-N yield replicated the measured data trend quite well (**Figure 2**), the model underestimated the measured values during the autumn-winter 2005/2006 when high nitrate levels in stream were observed [16]. This fact may be due to underestimation of some discharge peaks in this period [21], which led to underestimating corresponding NO_3-N yield because NO_3-N, like other water quality parameters, depends on hydrological processes, and therefore errors in discharge simulations are magnified in their simulation. Other authors (e.g., [3, 4, 23]) using the SWAT model also attributed the unsatisfactory NO_3-N simulations to problems in discharge simulations. This should be considered a weakness of SWAT to perform NO_3-N simulations at high discharge rates, especially in small streams, such as Corbeira, due to wide variations of discharge and nutrient concentrations during runoff events.

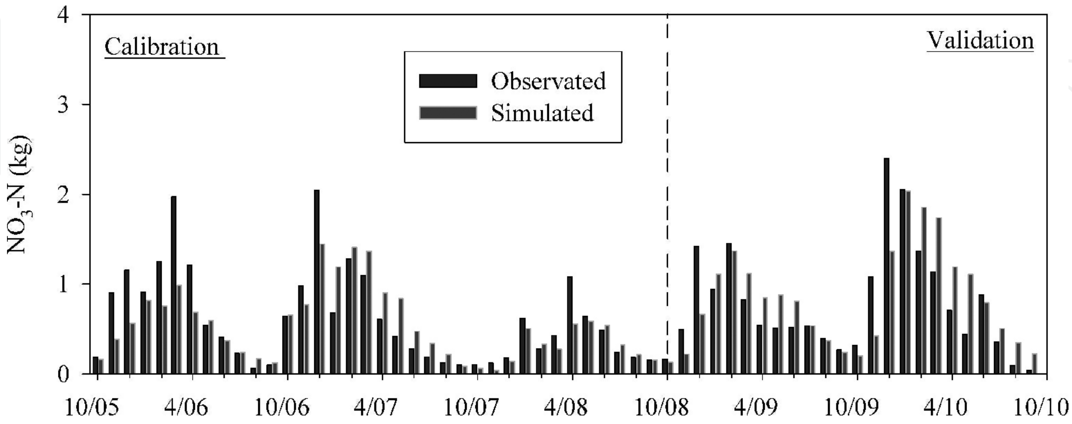

Figure 2. Measured and estimated monthly nitrate yield during the study period. Black broken line marks the separation between the calibration and validation periods.

Annual NO_3-N yield showed high inter-annual variability, ranging from 5.6 kg ha^{-1} in 2005/2006 to 2.8 kg ha^{-1} in 2007/2008. The mean annual NO_3-N measured at the Corbeira catchment outlet was 4.8 kg ha^{-1}, which is comparable with the mean simulated value of 5.1 kg ha^{-1}. The model simulates the NO_3-N yield at monthly and annual scale with sufficient accuracy, indicating that the SWAT model is an appropriate tool for simulating nitrate discharge under the conditions prevailing in the Corbeira catchment. It could be a useful tool for predicting the effect of land use and climate change on NO_3-N yield. Its usefulness could be extended to evaluating management plans aimed at implementing the Water Framework Directive [8] in the Corbeira catchment and in areas with similar environmental and geomorphological conditions. For such purposes, it is essential nutrient yield to be estimated precisely, otherwise results from the model become more uncertain [9], with the consequent impact on environmental management plans. In the Corbeira catchment, it was found that NO_3-N yield, and especially those of particulate phosphorus, exhibited wide variability depending on the sampling technique, method of calculation and evaluation period. It was also seen that the monthly and fortnightly sampling widely underestimated nutrient loads, mainly particulate phosphorus [24, 25]. If data loads not reflecting reality are used, model calibration will be guided to the incorrect setting, as was shown by Ullrich and Volk [9] and Rodríguez-Blanco et al. [25], among others.

3.2. Nitrate yield from the different land uses

Nitrate yield is strongly influenced by land uses within a catchment. To evaluate the diffuse sources of pollution and quantify the nitrate yield entering the catchment from different land uses, the contribution of these to nitrate yield was investigated. This will help to identify the critical land use type and areas for nitrate loss, which is of vital importance in designing catchment management plans aimed at reducing nitrate losses in this type of landscape. **Figure 3** shows the spatial distribution of nitrate yield at HRU scale in the Corbeira catchment. It was observed that the spatial patterns of NO_3-N yield varied significantly in the catchment. The highest nitrate yields were recorded in cultivated areas (17.6 kg ha^{-1} $year^{-1}$) and pastures (13.5 kg ha^{-1} $year^{-1}$), whereas the lowest values were obtained in forest areas (1.98 kg ha^{-1} $year^{-1}$). These results clearly indicate that NO_3-N loss increases with agricultural land use. In fact, cultivated land exported 1.2 and 9 times more nitrate than pastures and forest lands, respectively. The simulated results were comparable to the values reported by other authors in agricultural catchments. Thus, Ferrant et al. [3] found NO_3-N losses of 13 kg ha^{-1} $year^{-1}$ in a small, intensive agricultural catchment in France. Similarly, Frink [26] indicated NO_3-N losses of 3.5–15 kg ha^{-1} $year^{-1}$ from pastures.

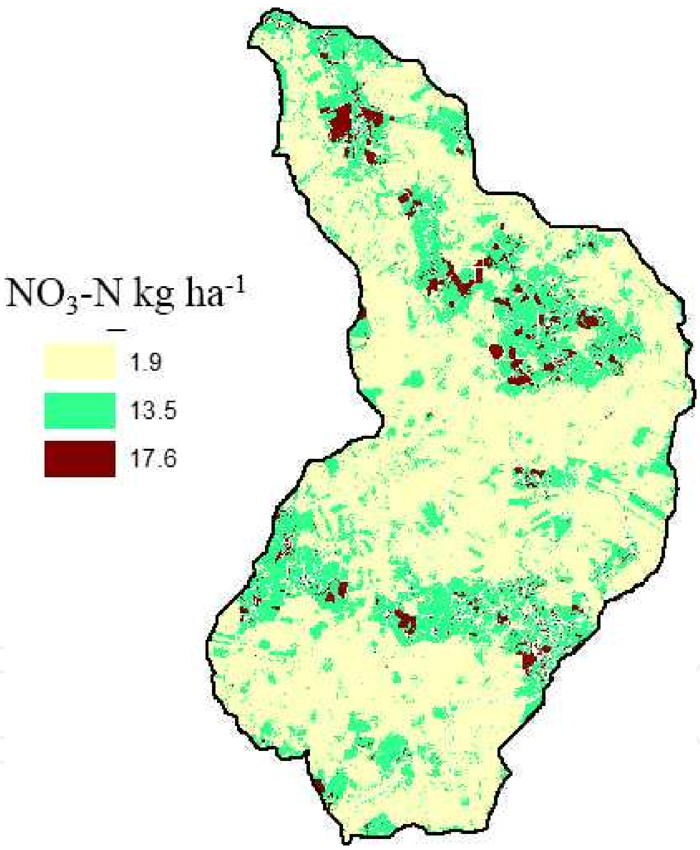

Figure 3. Spatial distribution of nitrate yield in the Corbeira catchment.

The analysis of the contribution of land uses to NO_3-N yield revealed that agricultural lands (pastures and cultivated lands), despite representing only 30% of the catchment area, were the dominant contributor to the total nitrate yield (77%), whereas the forest area (65% of the catchment area) had little influence on nitrate yield in comparison with the other land use. This is mainly due to agricultural land receiving a supply of nitrogen fertilizers (mostly slurry) significantly higher than that of forest land. Therefore, measures aimed at reducing nitrate losses in the catchment should focus on agricultural areas, especially in the pastures, since they are the main area source of NO_3-N area in the Corbeira catchment (64% of total nitrate yield). The above results show the usefulness of SWAT to evaluate the spatial distribution of nitrate yield and identify the most sensitive areas to nitrate pollution within the catchment. Therefore, it would be a very useful tool for evaluating the influence of alternative management practices in controlling nitrate losses, which is in line with the requirements of WFD.

3.3. Transport pathways of nitrate yield

To evaluate the major processes controlling nitrate transport, the contribution of flow component to nitrate yield was evaluated. It was observed that in the Corbeira catchment about 63% of the nitrate load was transported in groundwater, 27% in lateral flow and the remaining 10% via surface runoff. These results are in accordance with previous studies by Rodríguez-Blanco et al. [16] who found that groundwater is the dominant pathway for nitrate in the study catchment, accounting for 60% of total nitrate losses. These results are also in agreement with the studies by Lam et al. [4] and Hu et al. [27], among others, who reported that the groundwater was the major pathway for NO_3-N in areas located in humid zones. These results suggest that management practices aimed at reducing the nitrate load from agriculture in the Corbeira catchment, and in other areas with similar climate, geomorphological and land use characteristics, should mainly focus on reducing the NO_3-N leaching in the catchment.

4. Summary and conclusions

The results from the present study showed an existence of an agreement between measured and model estimations of nitrate yield at catchment outlet, although SWAT underestimated the measured values during some months in the calibration period. The mean annual measured NO_3-N yield was 4.8 kg ha^{-1}, whereas the mean annual simulated NO_3-N yield was 5.1 kg ha^{-1}. The model performance was satisfactory ($R^2 > 0.5$; NSE > 0.5 and PBIAS < 10%) in both calibration and validation periods, indicating that SWAT is an appropriate tool for simulating nitrate discharge under the conditions prevailing in the Corbeira catchment and, consequently, in catchments of similar topography, soil, land use, climate and management. A large spatial variability in the NO_3-N yield was observed within the catchment. As expected, cultivated land had the highest NO_3-N loss (17.6 kg ha^{-1}) and the forest had the lowest (1.98 kg ha^{-1}), indicating that NO_3-N loss increases with agricultural land use. Agricultural land (pasture + cultivated land) accounted for 77% of the NO_3-N losses although they represent only 30% of the catchment area, the pasture being the major contributor of total NO_3-N yield (64%). The results also indicated that groundwater was the major nitrate transport pathway within the catchment, accounting for 63% of the total NO_3-N yield. Lateral flow and surface runoff accounted for 27% and 10% of the NO_3-N yield, respectively. Based on these results, management practices in this catchment should be focused on reducing the leaching of nitrate from agricultural land.

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