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Simulating Land Management Options to Reduce Nitrate Pollution in an Agricultural Watershed Dominated by an Alluvial Aquifer

Itsasne Cerro,* Iñaki Antigüedad, Raghavan Srinavasan, Sabine Sauvage, Martin Volk, and José Miguel Sanchez-Perez

The study area (Alegria watershed, Basque Country, Northern Spain) considered here is influenced by an important alluvial aquifer that plays a significant role in nitrate pollution from agricultural land use and management practices. Nitrates are transported primarily from the soil to the river through the alluvial aquifer. The agricultural activity covers 75% of the watershed and is located in a nitrate-vulnerable zone. The main objective of the study was to find land management options for water pollution abatement by using model systems. In a first step, the SWAT model was applied to simulate discharge and nitrate load in stream flow at the outlet of the catchment for the period between October 2009 and June 2011. The LOADEST program was used to estimate the daily nitrate load from measured nitrate concentration. We achieved satisfactory simulation results for discharge and nitrate loads at monthly and daily time steps. The results revealed clear variations in the seasons: higher nitrate loads were achieved for winter (20,000 kg mo^{-1} NO_3–N), and lower nitrate loads were simulated for the summer (<1000 kg mo^{-1} NO_3–N) period. In a second step, the calibrated model was used to evaluate the long-term effects of best management practices (BMPs) for a 50-yr period by maintaining actual agricultural practices, reducing fertilizer application by 20%, splitting applications (same total N but applied over the growing period), and reducing 20% of the applied fertilizer amount and splitting the fertilizer doses. The BMPs were evaluated on the basis of local experience and farmer interaction. Results showed that reducing fertilizer amounts by 20% could lead to a reduction of 50% of the number of days exceeding the nitrate concentration limit value (50 mg L^{-1}) set by the European Water Framework Directive.

In regions with intense agricultural management, surface and groundwater are subjected to contamination by inputs of fertilizers and pesticides. Nitrate leaching from agricultural land is a common problem in many European countries with intensive agricultural production (Rode et al., 2008; Volk et al., 2009). Hence, regulations such as the European Water Framework Directive (WFD) aim to achieve a good ecological status for water bodies. The first challenging deadline for achieving the environmental objectives of the WFD is 2015. The WFD requires a focus on river basins and surface water bodies as reference units as well as the use of reliable modeling tools to evaluate the contribution of nitrogen sources to water pollution, to quantify loads, and to evaluate alternative water management policies, all of which pose significant new challenges to water managers, planning authorities, researchers, and stakeholders (Dørge and Windolf, 2003; Wasson et al., 2003; Rekolainen et al., 2003; Volk et al., 2008).

This study focuses on the Alegria watershed (Basque Country, Spain), which is a flat lowland area with low hydraulic gradients and a high groundwater table. Such catchments are especially vulnerable to groundwater pollution (Lam et al., 2010; Schmalz et al., 2007; Muller et al., 2004). In such lowland watersheds, groundwater transport plays a key role in the transport of pollutants from the soils into the water system (Wriedt and Rode, 2006).

The hydrological processes of the Alegria watershed are dominated by an important alluvial aquifer. The water quality of the aquifer is strongly impaired by farming activities in the watershed (García-Linares et al., 2003; Sánchez-Pérez et al., 2003b; Martinez, 2011). From the beginning of the 1980s to the early 1990s, nitrate concentration increased dramatically up to 200 mg L^{-1} in the East Sector of the aquifer (Arrate et al., 1997; Sánchez-Pérez et al., 2003b). These values significantly exceed the limit value for nitrates (50 mg L^{-1} NO_3) as set the Nitrate Directive of the European Commission (91/676/CEE), which forms part of a comprehensive framework of EU legislation to protect the environment. Due to this situation,

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Abbreviations: BMP, best management practice; NVZ, nitrate-vulnerable zone; WFD, Water Framework Directive.

in 1999 the Basque Government designated this part of the aquifer as a nitrate-vulnerable zone (NVZ). A NVZ is an area of land that drains into the waters affected by nitrate pollution and waters that could be affected. Nitrate-vulnerable zones were introduced by the UK government in response to the proposal that EU countries must reduce nitrate levels in drinking water to a maximum of 50 mg L^{-1}. Consequently, an agricultural good practices and action plan was approved that should lead to a reduction of the nitrate concentration in the aquifer over time.

This polluted aquifer has a close connection with the stream, which is subjected to contamination risks, especially during flood events. This study is included in the Aguaflash European project (http://www.aguaflash-sudoe.eu), which evaluates the risks of deterioration of surface water quality in agricultural catchments, especially during floods.

In the case of nitrogen pollution, groundwater in lowland areas responds slowly to a given input situation. There is a need to investigate the system response to management changes through years. Model scenarios can be helpful in finding reasonable measures for achieving a better ecological status, taking into account possible changes of land and water use, management practices, and climate conditions (Hesse et al., 2008).

Several published studies have demonstrated the robustness of SWAT (Soil and Water Assessment Tool) in predicting nutrient losses at the catchment scale (Gassman et al., 2007; Ferrant et al., 2011). Saleh et al. (2000), Saleh and Du (2004), Santhi et al. (2001), Stewart et al. (2006), Di Luzio et al. (2002), and Boithias et al. (2012) evaluated SWAT by comparing SWAT nitrogen prediction with measured nitrogen losses. Borah and Bera (2003) found that SWAT was the most useful model for long-term simulation in predominantly agricultural watersheds. Furthermore, simulation of hypothetical scenarios in SWAT has proven to be an effective method of evaluating alternative land use, best management practices (BMPs), and other factors on pollutant losses (Gassman et al., 2007; Ullrich and Volk, 2009). According to these justifications, the SWAT model was applied in the Alegria watershed based on a database of hydrological data and quality data from October 2009 to June 2011. The main objectives of this study were (i) to simulate the water balance and the nitrate loads and (ii) to predict nitrate behavior in the river (using as reference the threshold of 50 mg L^{-1} NO_3) over long-term scenarios using different BMPs.

Materials and Methods

Study Area

The Alegria watershed is a subbasin of the Ebro river basin and is located in Basque Country (Northern Spain) at 3 km east of the city of Vitoria-Gasteiz (Fig. 1). The stream has a total length of 12 km, and the whole watershed area is about 113 km^2. From a geological point of view, this watershed is located within the Basque-Cantabrian basin and specifically in the Alava Platform domain (Rat, 1959). The flat part of the watershed is covered by quaternary materials, which are around 6 m in thickness, represented mainly by clays and silts with sand and gravel layers. The substratum is a marl material present around the watershed, coinciding with the highest topography areas of the catchment. They are impermeable marls of Lower Campanian (Martinez, 2011).

Approximately 75% of the watershed is used by intensive agriculture; the remaining 25% is covered by forests. Common agricultural practices in the watershed consist in annual rotation systems from dry crops (wheat, oat, and barley) to irrigated crops (sugarbeet and potato). The topography of most of the watershed is flat with slope gradients of <5% and an elevation range of 400 m. Climatic conditions are continental, with an annual average rainfall of 600 to 700 mm and high intra-annual temperature variability ranging from <0°C during winter to >25°C during summer. Although the hydrological processes of the watershed are controlled by the rainfall conditions, they are also regulated by the quaternary alluvial aquifer. The groundwater table is near surface (1–3 m), and the Alegria River is the only receiver of this aquifer (Martinez, 2011). According to the European Nitrate Directive (91/676/CEE), the Basque Government declared the majority of the watershed as a NVZ in the year 1999. The application of new rules in agricultural practices, such as dose limitation and changes on irrigation water source from groundwater to surface water, has improved water quality (Garcia Linares et al., 2003; Sánchez-Pérez et al., 2003b; Jégo et al., 2008). However, the alluvial aquifer still presents high nitrate contents, exceeding the limit value of 50 mg L^{-1} NO_3 (Martinez, 2011) and affecting the river water quality, especially during flood events. In fact, during this study period, an increase in the nitrate concentration was observed during flood events.

To supply the cities of Vitoria-Gasteiz and Bilbao with water, there is a channel that diverts all water from the upper part of the

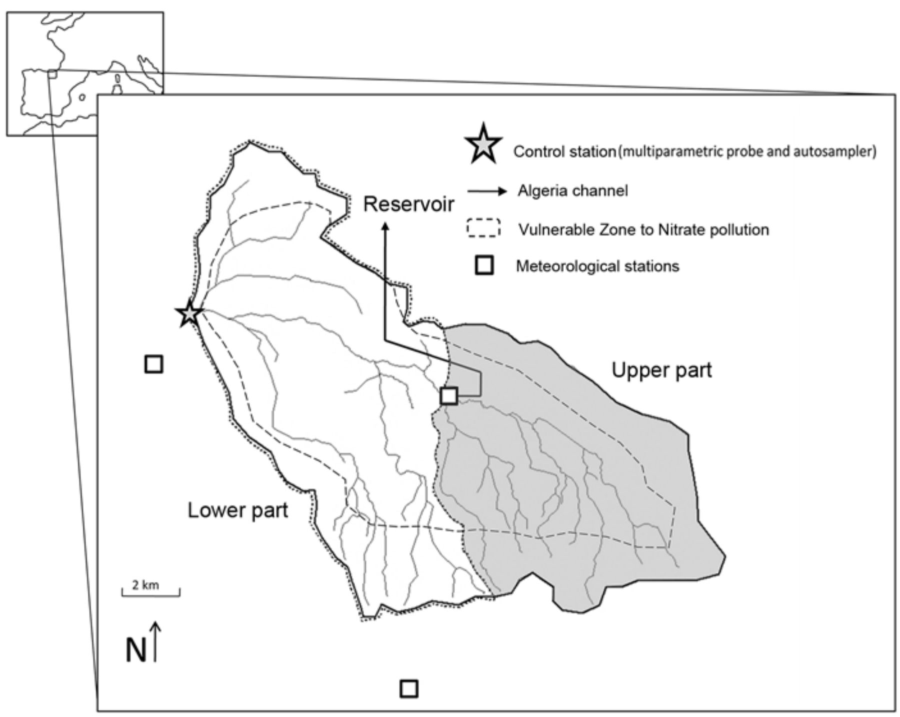

Fig. 1. Location of the Alegria catchment, meteorological stations, and designated nitrate-vulnerable zone.

watershed to the Ulibarri-Gamboa reservoir (Fig. 1). Therefore, the upper part of the watershed was not included in this study.

Monitoring of the Watershed

Water Quality

Water quality has been monitored at the outlet of the Alegria watershed (Fig. 1). The measurements were initiated with the beginning of Interreg Aguaflash European project (www.aguaflash-sudoe.eu) in October 2009. The objective of the project is to evaluate the risks of water quality deterioration in agricultural catchments, especially during floods.

The monitoring station consists of a multiparametric probe (YSI 6820), which continuously measures (each 10 min) parameters such as electrical conductivity of water (μS cm^{-1}), turbidity (NTU), temperature (°C), pH, dissolved oxygen (mg L^{-1}, %sat.), NO_3–N (mg L^{-1}), and river water level (m). The probe is connected to an automatic sampler that takes samples when the water level varies more than 0.30 m. In addition to this high-resolution dataset obtained during floods, manual sampling was performed weekly from October 2009 to June 2011. Water samples were filtered to analyze nitrate concentrations by ionic chromatography.

Hydrological Data

Discharge measurements were performed at the control station to obtain hydrological data in the lower part of watershed where no data were available before. A current meter was used to measure flow. Daily flow data were obtained directly from the rating curve built with discharge measurements, converting the water level (m) to discharge (m^3 s^{-1}). The equation has a good adjustment with low and mid-flows, but some doubts persist on very high flows.

Load Estimation

The LOADEST program has been used to estimate nitrate daily loads in the Alegria watershed outlet using observed weekly data. LOADEST is a FORTRAN program for estimating constituent loads in streams and rivers (Runkel et al., 2004). Eleven regression models can be used, some of which are set differently depending on the season chosen by the user. The model that provides the minimum variance is usually the best. If the normal distribution is verified, the adjusted maximum likelihood estimation (AMLE) can be used.

Observed flow was used in LOADEST to estimate the regression load. However, there were some uncertainties in the measured high flows. To reduce uncertainties, the calibrated SWAT flow was used because it seems to better capture the highs and lows.

SWAT Model

Model Description

We used the SWAT model because it is a basin-scale, continuous time model that operates on a daily time step and evaluates the impact of agricultural management practices on water, sediment, and chemical yields in ungauged basins (Arnold et al., 1998). The model is physically based, semidistributed, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple subwatersheds, which are subdivided into hydrologic response units that consist of homogeneous land use, slope, and soil characteristics (Neitsch et al., 2002).

The SWAT model monitors five different pools of N in the soils: two inorganic (NH_4^+ and NO_3^-) and three organic (fresh organic N associated with crop residue and microbial biomass, and the active and stable N pool associated with soil humus). Nitrogen may be added to the soil in the form of fertilizer, manure, or residue application. Plant uptake, denitrification, volatilization, leaching, and soil erosion are the major mechanisms of N removal from a field (Arabi et al., 2007).

The background for the crop growth and the management practices is the EPIC crop growth model (Williams et al., 1989), which was developed to simulate the impact of erosion on crop productivity and has evolved into a comprehensive agricultural management, field-scale, nonpoint source loading model (Neitsch et al., 2002; Ullrich and Volk, 2009).

Model Inputs

The main input data used for the SWAT model are shown in Table 1. The model uses topography information to delineate the watershed and define the river network. Once subbasins were defined, land use and soil maps were superimposed. Agricultural practice in this catchment involves 2-yr crop rotation, from dry crops (wheat, oat, and barley) to irrigated crops (sugar beet and potato). Information about fertilizer application and irrigation was included in the management operation. The cultivation schedule and the amounts of fertilizers and water applied are listed in Table 2.

Daily climatic data from 2002 to 2011 were obtained from three meteorological stations (Fig. 1) managed by the Basque Meteorology Agency. Precipitation, temperature, humidity, wind speed, and solar radiation data were obtained from all stations.

Model Set-Up and Calibration

The 53-km^2 watershed (corresponding to the lower part of the watershed shown in Fig. 1) was divided into 66 subbasins and 590 hydrologic response units. To obtain the best simulation for the Alegria watershed, it was necessary to carry out a detailed calibration process that was divided into the following steps: manual calibration, sensitivity analysis, model evaluation, and SWAT check.

Manual Calibration

The model was calibrated from October 2009 to November 2010, and the validation period was from November 2010

Table 1. Input data sources.

Data type	Source	Data description/properties
Topography	Geoeuskadi MDE LIDAR (2008)	digital elevation model (5 m × 5 m)
Soil map	Estudio Geomorfológico y Edafológico del Territorio Histórico de Bizkaia y Araba.	soil map for Alava (1:200,000)
Land use map	IKT (Basque Government)	land use classification
Climate data	Euskalmet, Basque Meteorology Agency	temperature, precipitation, wind speed, humidity, solar radiation (Kapildui, Arkaute and Alegria stations from 2002 to 2011)

to June 2011. Initial parameters were set up according to the watershed characteristics, which are strongly influenced by the alluvial aquifer. Whenever possible, parameters were determined from studies in the watershed. The initial amount of groundwater (SHALLST) was set at 6000 mm, and the threshold water level in the shallow aquifer for groundwater contribution to the main channel (GWQMIN) was set at 4500 mm (Arrate, 1994). SWAT models the movement of water into overlying unsaturated layers as a function of water demand for evapotranspiration. To avoid confusion with soil evaporation and transpiration, this process has been termed "revap." The revap coefficient (GW_REVAP) was 0.02, and the threshold water level in the aquifer for revap to occur (REVAPMN) was set to 5500 mm.

Initial nitrate concentration in shallow aquifer (SHALL_N) was set at 15 NO_3–N mg L^{-1}. A constant initial (SOL_NO_3) concentration of 20 mg kg^{-1} in soil layers was assumed (Martinez, 2011). Because nitrate fluxes strongly depend on water fluxes, parameters controlling water balance were calibrated as the first step, and only then was nitrate load considered (Pohlert et al., 2005).

Sensitivity Analysis

The sensitivity analysis method (Morris, 1991) assesses the most sensitive parameters for setting up the model in this catchment. Table 3 shows the main sensitive parameters for flow and NO_3–N, ranked according to Morris' analysis. Each parameter was automatically changed 10 times within the allowable range, which was selected once manual calibration was performed. The sensitivity analysis was performed for the calibration period (from October 2009 to November 2010).

Model Evaluation

To evaluate the accuracy of the model results, statistical methods such as Nash-Sutcliffe efficiency (NSE), Pearson's correlation coefficient (R), RMSE observations standard deviation ratio (RSR), and percent bias (PBIAS) were used. The NSE and R values range from 0 to 1, with 1 being the optimal

Table 2. Main crops and management practices.†

Crop	Sowing	Fertilizer application			Irrigation		Harvest
		Date	Type	kg ha^{-1} yr^{-1}	Date	mm $plot^{-1}$	
Wheat, oat, barley	1 Jan.	25 Jan 5 Apr.	15–15–15 NAC27	389 440	– –	– –	31 July
Sugarbeet	23 Apr.	20 Apr. 4 June	8–15–15 NAC27	766 440	28 June, 6 July, 17 July, 28 July, 4 Aug., 15 Aug., 8 Sept.	10	30 Oct.
Potato	28 Apr.	15 Mar 18 May	7–10–20 NAC27	1200 400	25 May, 5 June, 15 June, 25 June, 5 July, 15 July, 25 July, 5 Aug., 15 Aug.	10	1 Sept.

† Data from Neiker Public Agicultural Research Center

Table 3. Main sensitive parameters for flow and nitrates.

Variable	Description	Flow	Nitrates	Allowable range	Actual value used
Esco	soil evaporation compensation factor	1	4	0.8–0.95	0.9
Rchrg_Dp	deep aquifer percolation coefficient	2	2	0–0.1	0
Sol_K	saturated hydraulic conductivity of soil	3	1	0–400	1.76, 2.22, 7.9
Ch_K2	effective hydraulic conductivity in main channel alluvium	4	10	0–10	0
Gw_Delay	delay time for aquifer recharge	5	5	0.5–5	1
Alpha_Bf	base flow recession constant	6	6	0–1	0.35
Cn2	curve number	7	3	±10%	57, 75, 89
Surlag	surface runoff lag coefficient	8	8	0–8	5
Ch_N2	Manning's "n" value for the main channel	9	9	0.005–0.1	0.014
Slope	the mean slope within the HRU†	10	7	±10%	depends on the subbasin
Sol_Awc	available water capacity	11	11	4%	0.13–0.30
Nperco	nitrogen percolation coefficient	12	12	0–1	0.8
Usle_P	USLE equation support practice factor	13	13	0–1	1
Usle_C	minimum USLE cover factor		14	0.001–0.3	0.003, 0.2

† Hydrologic response units.

Table 4. Statistic summary.†

Model evaluation techniques	Flow				Nitrates			
	Monthly		Daily		Monthly		Daily	
	Cal.‡	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
Number data point used	12	8	391	191	12	8	391	214
Nash	0.87	0.95	0.68	0.49	0.66	0.85	0.63	0.88
COEF-correlation R	0.93	0.95	0.85	0.72	0.99	0.97	0.96	0.96
RSR	0.36	0.22	0.57	0.71	0.58	0.38	0.60	0.34
PBIAS	−4.35	15.02	−1.31	16.33	−26.98	2.13	−25.68	0.37

† Statistics values for nitrate simulation at daily time step were obtained by using moving average for 7 d.

‡ Calibration period: October 2009 to November 2010; validation period: November 2010 to June 2011.

value. The optimal value of RSR and PBIAS is 0; positive values of PBIAS indicate model underestimation, and negative values indicate model overestimation bias. Detailed information and definitions about statistics are described by Moriasi et al. (2007).

SWAT Check

The SWAT Check program was applied to identify different pathways for water and nitrogen. SWAT Check is a program that reads model output from the SWAT project and performs an overview of the watershed balance. There is more information of the program on the SWAT website (http://swatmodel.tamu.edu).

Scenario Development: Long-term Scenarios

The calibrated model was used to study the long-term effects of management operation changes to find options for water pollution abatement. The main goal was to reduce the input of NO_3^- into the groundwater and the river system. On the basis of the local experience and communication with local farmers, four different scenarios were established to reduce nitrate pollution and alleviate the water quality problem: scenario 1: maintaining existing management operations (reference scenario); scenario 2: reducing fertilizer application by 20%; scenario 3: splitting applications, same total amount of fertilizers but applied over the growing period in more than two applications; and scenario 4: reducing 20% of applied total fertilizer amount and splitting doses.

It is difficult to remove nitrate from groundwater; sometimes it takes several years or decades to improve the water quality, even years after reducing the fertilizer amounts (systems delay). In addition, risk assessments need long-term model runs to cover the existing weather variations. For these reasons, we have chosen a simulation period of 50 yr. Climatic data were obtained using temperature and precipitation series from the past 25 yr, including drought and wet years, and repeating them randomly at year scale.

Results and Discussion

Pathways (SWAT Check)

SWAT Check was used to identify different pathways for water and nitrogen. Concerning the water balance ratios, it is clear that groundwater influence is high in the Alegria watershed, where base flow is about 82% of the total flow. Concerning N losses, total fertilizer N applied is 235 kg ha^{-1}, from which 116 kg ha^{-1} is leached to the groundwater. These results were similar to the results reported by Jégo et al. (2008) in the same area and also similar to the data obtained in an alluvial aquifer located in Garonne floodplain (Jégo et al., 2012). This may indicate a problem for groundwater pollution in accordance with SWAT Check limits (nitrate leached is >30 kg ha^{-1}, and it is more than 25% of the fertilizer applied).

If groundwater is found to be the dominant flow component and has a high concentration of nitrates, the SWAT model confirms that shallow groundwater flow is the main source of nitrates in the stream.

Simulation of Flow and Nitrates

The most sensitive parameters for flow and nitrate transport are listed in Table 3. The ESCO parameter is related to the soil evaporation and has a significant impact on evapotranspiration, being the most sensitive parameter for flow. At the top of the ranking for nitrates, saturated hydraulic conductivity of soil (SOL_K) is found to be the most sensitive. Also, recharge to deep aquifer is a sensitive parameter, but in this case the substratum marls are impermeable, so this parameter was not taken into account for calibration.

A statistic summary was done, including monthly and daily values for different model evaluation techniques (Table 4). It was separated into calibration and validation periods for flow and nitrate load. SWAT performed very well for monthly flows (m^3 s^{-1}), showing E_{NS} and R values of 0.87 and 0.93, respectively, for the calibration period and 0.95 and 0.95, respectively, for the validation period at the outlet of the catchment. Also, PBIAS and RSR values indicate a very good agreement between observed and simulated flow at the monthly scale (Moriasi et al., 2007).

Looking at daily statistic values and according to Saleh et al. (2000), there is good agreement between daily observed and simulated flow for the calibration period, with E_{NS} and R values of 0.68 and 0.85, respectively. However, these values decreased to 0.49 and 0.72, respectively, for the validation period, indicating in this case the worst performance. This could be related to the lack of observed data about the flood events for the period of November and March. Figure 2 shows the observed and simulated daily discharge at the Alegria watershed outlet from October 2009 to June 2011. Peak flows were underestimated; the reason could be that observed flow during flood events was not perfectly estimated due to rating curve imprecision in high water conditions.

Regarding nitrate estimation, the SWAT model has performed better than expected. At the monthly scale, the agreement between observed and estimated N load (NO_3–N kg) is good

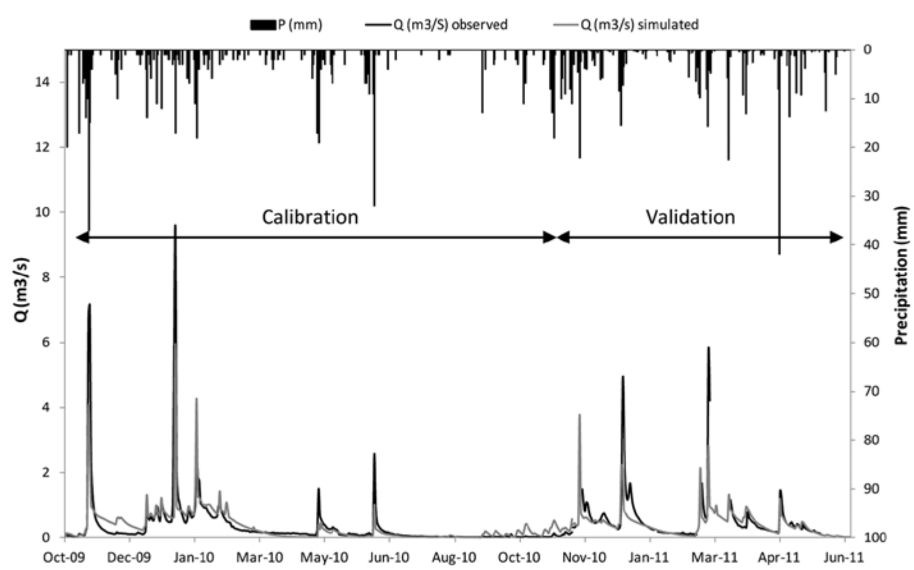

Fig. 2. Simulated and measured daily discharge at the Alegria Watershed outlet.

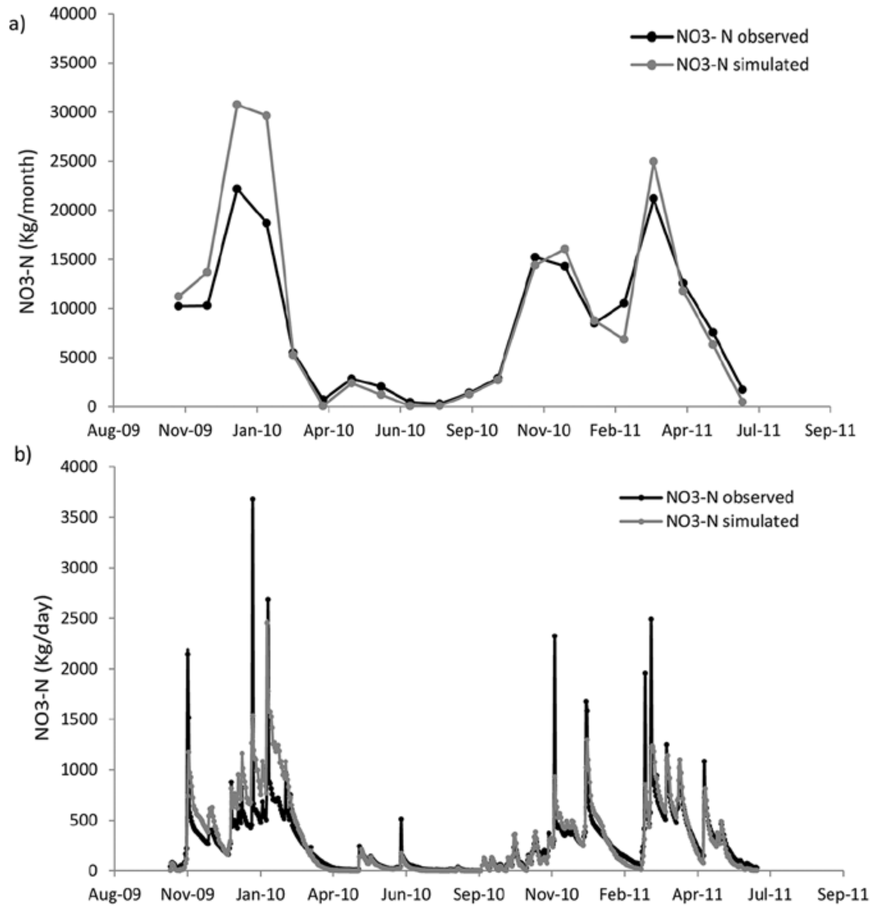

Fig. 3. Simulated and observed nitrate load (estimated by LOADEST) at monthly and daily time steps.

for the calibration period and, according to PBIAS evaluation, is very good for the validation period (Table 4) (Moriasi et al., 2007). Furthermore, N_{SE} and R coefficients were 0.66 and 0.99, respectively, for the calibration period and 0.85 and 0.97, respectively, for the validation period. Figure 3a shows the observed and simulated monthly NO_3–N loads (kg mo^{-1}). During winter, increased N loads can be observed, coinciding with an increased number of more flood events.

Daily statistic values for nitrate were obtained by determining the average over 7 d (Table 4). In this way, N_{SE} and R values show 0.63 and 0.96, respectively, for the calibration period and 0.88 and 0.96, respectively, for the validation period. In this study, we assumed daily and monthly E_{NS} values to be satisfactory when they were higher than 0.36 (Van Liew and Garbrecht, 2003) and daily and monthly R values to be satisfactory when they were higher than 0.5 (Green et al., 2006). Figure 3b shows the observed and simulated nitrate loads at a daily scale. The observed nitrate peaks coincide with flood events, probably indicating a groundwater source. Nitrates accumulated in the aquifer are pushed by the rainfall during floods.

Long-term Scenarios

Figure 4 shows the nitrate concentration (NO_3^-, mg L^{-1}) values in the river water for four different scenarios for the 50-yr period after 2007. A seasonal variability can be observed: Nitrate concentrations are higher in the winter period, coinciding with more flood events and lower plant uptake. During a drought period of some years

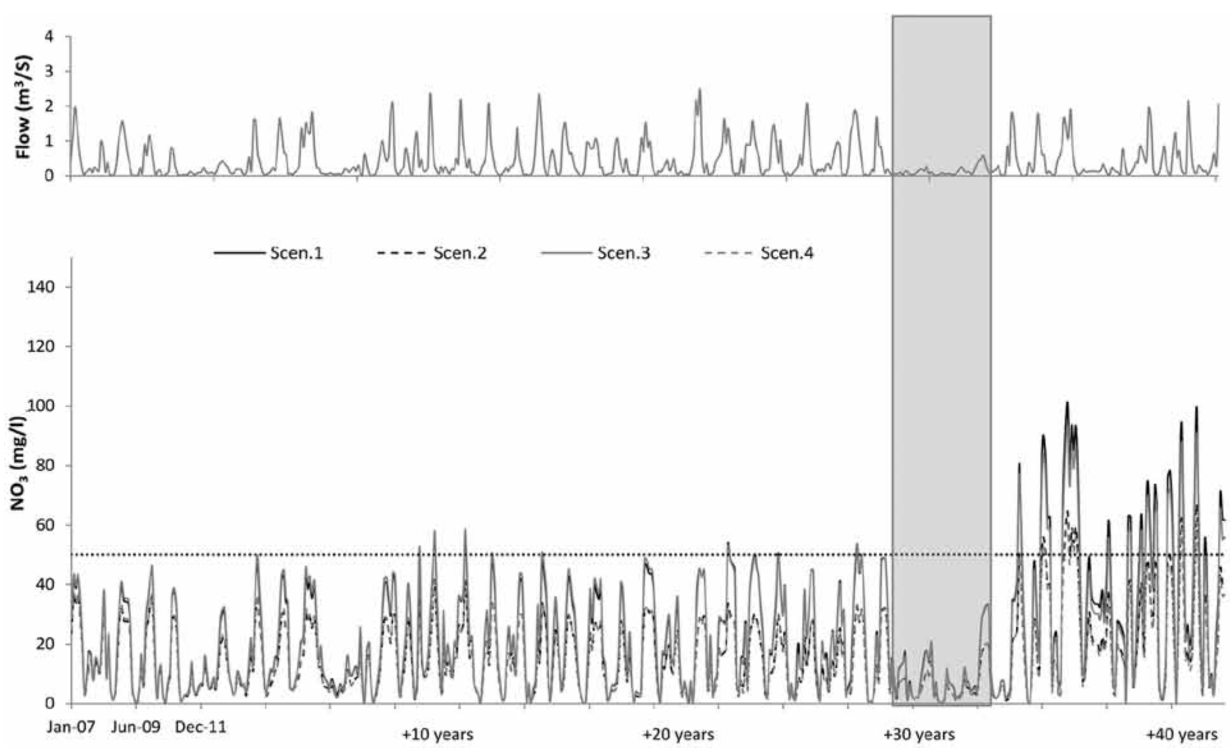

Fig. 4. Nitrate concentration (mg L^{-1}) on river water for four different scenarios (50-yr period).

Table 5. Nitrogen applied, nitrogen leached, and crop yield for long-term scenarios.

	Scenario 1: no management changes	Scenario 2: reducing 20% fertilizer amount	Scenario 3: same total fertilizer amount, but splitting doses	Scenario 4: reducing 20% fertilizer amount and splitting doses
Total fertilizer N applied, kg ha^{-1}	218	178 (−18%)†	218 (0%)	176 (−19%)
N leached to the groundwater, kg ha^{-1}	108	71 (−34%)	104 (−3%)	68 (−37%)
Crop yield, Mg ha^{-1}	5.8	5.6 (−3%)	5.5 (−5%)	5.2 (−10%)

† The percentage corresponds to the difference observed compared with scenario 1.

(marked in the graph), there is less flow and fewer nitrates in the river. In this period, N applied accumulates in the aquifer. With a new raining period of some years, more flow is generated and leads to an exponentially increased nitrate concentration for the following years. Nitrate concentration increments are higher when the drought period is longer; thus, the alluvial aquifer acts as storage for nitrates.

Table 5 depicts total fertilizer N applied (kg ha^{-1}), N leached to the groundwater (kg ha^{-1}), and crop yield (Mg ha^{-1}) for the different scenarios. By reducing fertilizer application by 20% (scenario 2), the amount of N leached to the groundwater is reduced by 34%, and there would be only a 3% reduction of crop yield. Splitting doses (scenario 3) led to a reduction of 5% of crop yield, but only 3% of the N that is leached to the groundwater can be observed. Applying both practices (scenario 4), the amount of N leached is reduced by 37%, and crop yield is reduced by 10%.

Figure 5 shows daily nitrate concentration percent exceedance probability curves (mg L^{-1}) for four different future management scenarios. The probability of exceeding the limit values of the European Nitrate directive (50 mg L^{-1}) decreased by reducing the applied fertilizer amount by 20% fertilizer (scenarios 2 and 4); this limit value was exceeded only 5% of the time. However, by maintaining the total N amount but splitting doses (scenario 3), no differences can be seen in comparison to scenario 1. In both cases, the probability of exceeding the limit value is higher than 10%. Hence, a decrease of 20% of the applied fertilizer amount (scenarios 2 and 4) would lead to a reduction of 50% of the number of days with nitrate concentration higher than 50 mg L^{-1}.

Conclusions

The Alegria watershed serves as an example for agricultural lowland areas strongly influenced by an alluvial aquifer. The watershed is located within a NVZ. Groundwater is affected by nitrate pollution coming from fertilizer excesses. In this study, the agro-hydrological model SWAT was applied to simulate discharge and nitrate load in stream flow at the outlet of the catchment and to find a management option for water pollution abatement.

Despite the high influence of groundwater in the river system, statistic values revealed that simulations of flow and nitrate were performed satisfactorily, showing a good agreement between simulated and measured discharges and nitrates, at monthly and daily time steps at the outlet of the watershed. Estimation of daily nitrate load was performed by using the LOADEST program, which converted measured nitrate concentration to daily load.

Looking at the different pathways for water and nitrogen, the groundwater was found to be the dominant flow component, with high nitrate contents. The SWAT simulations confirmed that shallow groundwater flow is the main source of nitrates to the stream. Seasonal behavior was described, showing higher nitrate loads in the winter. This is related to flood events and lower plant nutrient uptake, which leads to the transport of the polluted groundwater to the river.

Four different management scenarios were simulated with SWAT to study the long-term effects of nitrate pollution in the Alegria watershed over 50 yr. SWAT demonstrated that the alluvial aquifer acts as short- and long-term transient storage of nitrates. During drought periods of some years, the applied N is stored at the aquifer and is then transported to the river in periods with more flow. After the drought years, high nitrate concentrations can be observed (the most important being the simulated period for all the scenarios), whereas discharge is not significantly different.

Scenario 2 (reduction of 20% of the fertilizer applied) was found to be the best BMP, which led to a reduction (i) of 18%

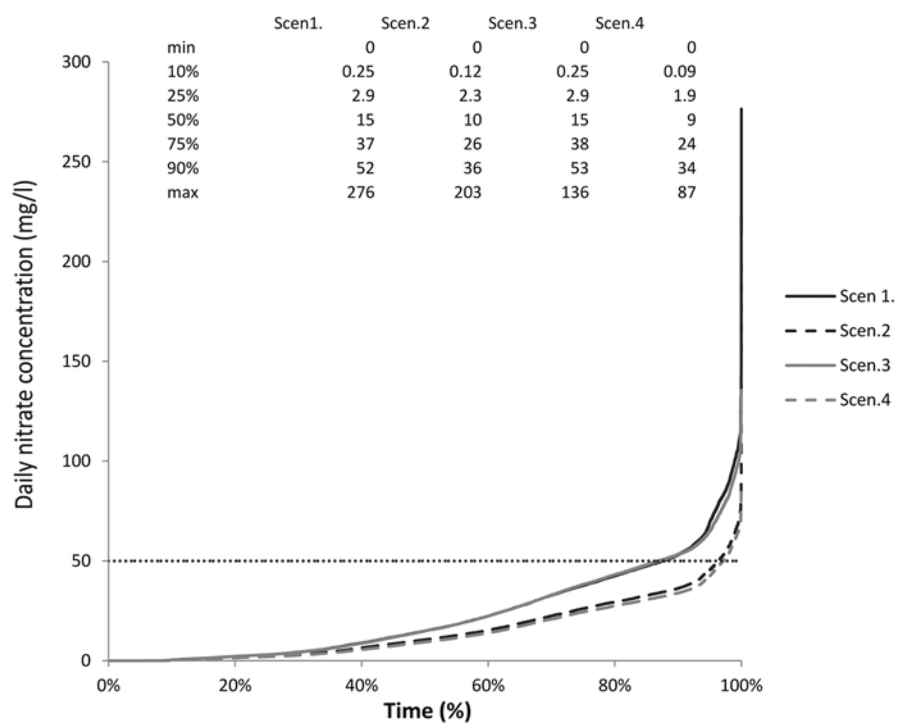

Fig. 5. Daily nitrate concentration percent exceedance probability curves (mg L^{-1}) for four different scenarios.

of N applied, (ii) of 34% of N leached to the groundwater, (iii) of 3% of crop yield, and (iv) of 50% of the number of days with nitrate concentration higher than the European threshold (50 mg L^{-1}).

Best management practice modeling via long-term scenarios is subject to uncertainty due to changes in agricultural practices and climate change. Nevertheless, the results could add to our understanding of the overall effect of BMPs in agricultural lowland areas strongly influenced by an alluvial aquifer.

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