Understanding nitrogen transfer dynamics in a small agricultural catchment: Comparison of a distributed (TNT2) and a semi distributed (SWAT) modeling approaches

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ARTICLE INFO

Keywords:
Agriculture
Nitrogen losses
Small catchement modeling

SUMMARY

The coupling of an hydrological and a crop model is an efficient approach to study the impact of the interactions between agricultural practices and catchment physical characteristics on stream water quality. We analyzed the consequences of using different modeling approaches of the processes controlling the nitrogen (N) dynamics in a small agricultural catchment monitored for 15 years. Two agro-hydrological models were applied: the fully distributed model TNT2 and the semi-distributed SWAT model. Using the same input dataset, the calibration process aimed at reproducing the same annual water and N balance in both models, to compare the spatial and temporal variability of the main N processes. The models simulated different seasonal cycles for soil N. The main processes involved were N mineralization and denitrification. TNT2 simulated marked seasonal variations with a net increase of mineralization in autumn, after a transient immobilization phase due to the burying of the straw with low C:N ratio. SWAT predicted a steady humus mineralization with an increase when straws are buried and a decrease afterwards. Denitrification was mainly occuring in autumn in TNT2 because of the dynamics of N availability in soil and of the climatic and hydrological conditions. SWAT predicts denitrification in winter, when mineral N is available in soil layers. The spatial distribution of these two processes was different as well: less denitrification in bottom land and close to ditches in TNT2, as a result of N transfer dynamics. Both models simulate correctly global trend and inter-annual variability of N losses in small agricultural catchment when a sufficient amount data is available for calibration. However, N processes and their spatial interactions are simulated very differently, in particular soil mineralization and denitrification. The use of such tools for prediction must be considered with care, unless a proper calibration and validation of the different N processes is carried out.

1. Introduction

Human activities have significantly altered the global nutrient cycle in temperate areas such as Northeastern United States (Howarth et al., 1996; Berka et al., 2001; Boyer et al., 2002), New Zealand (Gillingham and Thorrold, 2000; Monaghan et al., 2005), Ireland (Neill, 1989; Watson and Foy, 2001) and United Kingdom (Webb and Walling, 1985; Reynolds and Edwards, 1995; Whitehead et al., 2002b), Norway (Blecken and Bakken, 1997), and France (Ruiz et al., 2002; Molenat et al., 2002; Martin et al., 2004). Global approaches have been used to get an overview of anthropogenic impacts on water quality. Alvarez-Cobelas et al. (2008) studied nitrogen (N) export rates from 946 rivers around the world as a function of quantitative and qualitative environmental factors such as land-use, population density, dominant

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hydrological processes. They concluded that regional modeling approaches are more useful than global large-scale analyzes. The N cycle at the field scale (Recous et al., 1997) and transport dynamics at the catchment scale are relatively well known (Whelan and Kirkby, 1995), but there is a need to understand direct interactions between land cover and water pollution by nutrient in space and time. Internal processes of N cycle could be dominant over external modification (Webb and Walling, 1985). Many results highlight the poor correlation between N losses by agricultural soils and nitrate concentrations in stream water (Böhlke and Denver, 1995; Modica et al., 1998; Puckett and Cowdery, 2002; Molenat et al., 2002; Ruiz et al., 2002; Martin et al., 2004). Petry et al. (2002) have demonstrated that the nitrate concentration is mainly controlled by hydrological conditions. Probst (1985) and Kattan et al. (1986) have shown respectively in Garonne and Mosel basins that the annual N-exportation rates (ratio between N river exportation and N fertiliser inputs) are proportionnal to river discharge. Ohte et al. (2003) and Martin et al. (2004) showed that groundwater nitrate concentration distribution is controlling seasonal nitrate variation in the stream, Lapworth et al. (2008) showed that the shallow groundwater is both a source and a sink for dissolved N, and that reducing conditions of riparian areas are important in controlling N transformations.

Breuer et al. (2008) have made a non-exhaustive review of widely used hydro-biogeochemical mesoscale catchment models. In that scope, the coupling of an hydrology and a crop model seems to be an efficient approach in intensive agricultural context to study the impact of the interactions between agricultural practices and catchment physical characteristics on the dynamics of N attenuation in streams (Mangold and Tsang, 1991; Vachaud et al., 1993; Styczen and Storm, 1995; Lunn et al., 1996; Beaujouan et al., 2002; Whitehead et al., 2002a; Wade et al., 2004; Liu et al., 2005; Flipo et al., 2007).

Coupled models have thus been developed and used since the 1980s to simulate N transformation at the field scale (SOILN (Johnsson et al., 1987), WAVE (Vanclooster et al., 1995), LEACHN (Jabro et al., 1995), CREAMS (Kinsel, 1980)) or nitrate transfer at the catchment scale, (e.g. ANSWERS (Beasley et al., 1980)). Many models have then been designed to study N dynamics and spatial interactions at the catchment scale, using different level of details and different space and time discretisation scheme (e.g. CATCHN (Cooper et al., 1994), CWSS (Reiche, 1994), DAISY/MIKE-SHE (Styczen and Storm, 1993; Christiaens and Feyen, 1997; Refsgaard et al., 1999), NMS (Lunn et al., 1996), SWAT (Arnold et al., 1998), INCA (Whitehead et al., 1998; Durand, 2004; Granlund et al., 2004), SHETRAN (Birkinshaw and Ewen, 2000), TNT2 (Beaujouan et al., 2002), DNMT (Liu et al., 2005)).

Recent studies show that the accuracy for the simulation of non-point source pollution of streams can be improved through the coupling of more detailed N transformation models within semi-distributed hydrological models (Borah and Bera, 2004; Li et al., 2004).

Our aim was to analyze the consequences of using different modeling approaches on the simulation of N dynamics in small agricultural catchments. In that scope we used two models which were designed with a focus on N processes (rather than on the hydrology) and with similar level of spatial and temporal resolution for the simulation of field scale processes: TNT2 and SWAT. We tested both models on a small agricultural catchment monitored for 15 years in South of France.

2. Material and methods

2.1. study site and study period

The Montoussé catchment at Auradé (Gers, France) is an experimental research site studied in collaboration with the fertilizer manufacturer GPN-TOTAL. Nitrate measurements were started in 1985 by AZF Toulouse (now GPN) to assess the impact of agricultural practices and landscape management on nitrate concentrations in streams. The Montoussé stream was selected for intensive survey because of its fast hydrological response and the intensive agricultural context. It is a tributary channel of the Save River, itself a left tributary of the Garonne River, located in Gascogne, an intensively cultivated region in south-west France (Fig. 1). The general characteristics are summarized in Table 1: the catchment is small, hilly and 88.5% of the surface is used for agriculture. The substratum consists of impervious Miocene molassic deposits. Only a shallow aquifer is present, since the substratum is rather impervious (clays) except some sand lenses that supply springs. Agriculture is mainly a sunflower and winter wheat succession with mineral fertilization.

During the study period (October 1985–September 2001), dry years (1986–1990) were followed by more humid years (1992–1996) (Table 2). The 'Gers' district is under the influence of a oceanic climate, which is characteristic of western France, and sometimes influenced by the Mediterranean climate. The mean annual rainfall during the study was 656 mm, with a maximum daily rainfall of 90 mm. Few daily rainfalls exceed 40 mm. Intensive rainfall is often observed during spring or autumn and generate large runoff events. Mean year temperature is 14.5 °C, with minimums around 0–1 °C in winter and maximums about 29–30 °C in summer.

During the last decade, good management practices have been carried out to decrease N leaching from soil and nitrate transfers to the stream. The more significant actions were raising farmers awareness about the best use of mineral fertilizers, the implementation of rye-grass and poplar stripes along the stream and ditches, and a delay in the burying of straws after harvest. The efficiency of each action has not yet been evaluated.

2.2. Agricultural practice survey

The agricultural practices have been surveyed by the 'Association des Agriculteurs d'Auradé' for the whole study period by yearly inquiries of farmers and field observations. Dates of plant sowing, tillage operations, fertilizer application and crop harvest, amount of fertilizer applied, crop yields are given for each agricultural plot, each year since 1992. The average yields for durum wheat, bread wheat, sunflower were, respectively, 5.2, 6.3 and 2.4 ton ha^{-1}. The average quantity of fertilizer applied were 182, 154 and 30 kg N ha^{-1} y^{-1} respectively for durum wheat, bread wheat and sunflower. Sunflower is generally sown in April and harvested in October, winter wheat is sown in November and harvested in July. Fertilizer are applied between January and April, sometimes in May for winter wheat. Winter wheat – sunflower succession implies a long period of bare soil between the harvest of wheat in July and the sowing of sunflower in March or April. No irrigation practicies are observed in this catchment. Even if the the farming system is simple and homogeneous, this data base is not complete. Some uncertainties remain, especially regarding the dates of fertilizer applications and possible variations between plots.

2.3. Nitrate concentration and water discharge survey

Nitrate concentration and water flow were surveyed from 1985 to 2004 at the catchment outlet. The discharge was measured continuously by DIREN (Direction Régionnale de l'Environnement) and rainfall was monitored with a tipping bucket rainfall station within the catchment. The concentrations of nitrate are known to vary within a day during and after major rainfall event. A typical sequence in the concentration signal observed is:

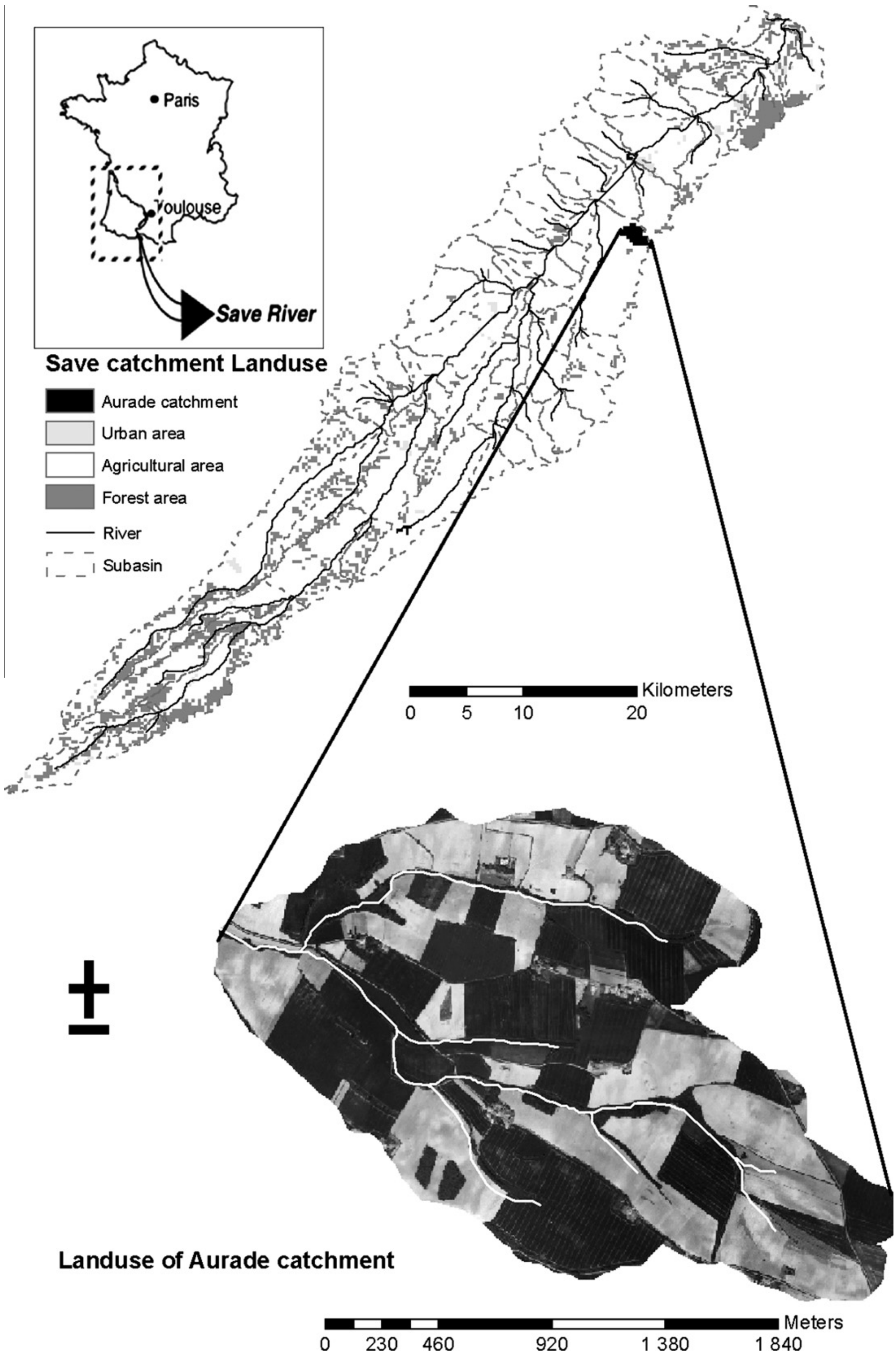

Fig. 1. Study site location within the Save river basin. Stream network and landuse of the study site of Auradé (aerial photo, cartoexplorer; IGN).

- a first weak dilution during runoff discharge (one to few hours),
- a concentration peak when lateral flow coming from the soil are reaching the stream,
- a period of decrease to the initial nitrate concentration when the base flow contribution is becoming dominant again.

Each sequence could be more or less important depending on the storm event, season and precedent rainfall. Dilution is directly depending on the amount of runoff generated during the rain event. The concentration peak could be intense and large (with some rare peaks around 100 mg $N—NO_3^-$ and a duration

Table 1
Characteristics of the Auradé catchment. Information on topography is derived from the DEM, land use distribution is computed from aerial photo (Cartoexplorer IGN) and climate data are an in situ measurement.

Parameter Topography	Value	Parameter Land use	Value
Area	3.35 km^2	Cultivated crop	86%
Max elevation	276 m a.s.l.	Pasture	2.1%
Mini elevation	172 m a.s.l.	Grass/poplar band	2.5%
Mean slope	9.3	Forest	5.2%
Max slope	28.8	Residential area	4.2%
Climate		River load	
Annual rainfall	656.5 mm	Mean [No_3^-]	11 mg N l^{-1}
Annual discharge	106.9 mm	Max [No_3^-]	32.2 mg N l^{-1}
Annual temperature	14.5 °C	No_3^- river load	13.3 kg N ha^{-1} y^{-1}

Table 2
annual water balance of the study period.

Year	Annual rainfall (mm)	Discharge/rainfall (%)
1986	497.6	20
1987	595.3	13.4
1988	700.83	17.7
1989	399.5	17
1990	490.1	5.7
1991	773.1	11.2
1992	729.3	14.4
1993	844	27.2
1994	778.7	33
1995	623.95	22.2
1996	689.8	16.9
1997	643.3	14.5
1998	570.35	6.8
1999	679.3	6.9
2000	730	12.1
2001	759.2	14.7

until few days) to unexistant, depending on previous flood events.

The sampling protocol setted up in 1985 to monitore nitrate concentration during a long time period has been designed to characterize this infra daily concentration dynamics. The frequency of sampling for nitrate concentration measurement was controlled by the volume of water discharged, using an ISCO 3700 Portable Sampler. A weekly visit was ensured to sample the river water by hand and check the previous week hydrograph. Samples were selected from the ISCO sampler in case of a flood event, one corresponding to base flow just before the water level increase, those corresponding to the storm event, and one corresponding to the recovery of the water level. At the laboratory, water samples were filtered, then kept in the dark and refrigerated at 4C, before being analyzed for $N-NO_3^-$ with High Performance Liquid Chromatography (HPLC). This sampling protocol has been followed by two technician during the study period and has not been modified in the phylosophy. 2834 days among the 5814 days of the study period have been sampled with a minimum of one sample per day for nitrate concentration. Some major flood events have been followed at 1 hour time step.

As we are using two agro-hydrological models at a daily time step and that rainfall datas were available at a daily time step, we have computed a daily nitrate concentration based on the linear interpolation of each concentration recorded in a day.

Fig. 2 show the daily concentration for days when there is measurement. The water yield varied during the study period (Table 2). The hydrograph shows extreme flood events (Fig. 2). The maximum daily water flow measured was 628 L s^{-1}, and the peak flows of the major seven events was over 200 L s^{-1}. Base flows are contrasted between humid and dry years, with a maximum of 50 L s^{-1} in winter 1993 and a maximum of 5.5 L s^{-1} in winter 1990. The nitrate concentrations are high with an overall mean concentration of 11 mg $N-NO_3^-$ (max and min of 32.2 mg N l^{-1} and 1.2 mg N l^{-1}). Highest concentrations are observed during spring and summer after an increase during the end of winter. These concentrations are associated with high discharge in spring and low flow period in summer. Nitrate concentrations then decrease to an annual minimum of 5–7 mg N l^{-1} between the end of summer and the begin of winter.

2.4. Soil description

A soil mapping of the catchment was carried out in 2006 by Sol-Conseil and EcoLab. Twelve soil types were defined for the catchment. Two of them are in lower part of the catchment and are deeper (2 m) than soils in the middle slope (1 m depth). The deepest soils have 2.1% of organic matter in the first layer (0–20 cm), and 1.2% up to 45 cm. The other soils generally contain around 2% of organic matter in the first layers, decreasing with depth to 0.5% at 30 cm. Most of soils contain 30–42% of clay in the first layers, increasing generally with depth. The soil characteristics have been used to set most of the soil and aquifer parameters in both models.

2.5. Model description and applicability

2.5.1. Rational behind the choice of two models

TNT2 has been chosen because the crop and hydrological modules are entirely distributed. It had been designed, calibrated and validated for north-western European catchment conditions (Beaujouan et al., 2002; Viaud et al., 2005; Oehler et al., 2009) where hydrology is driven by shallow aquifers (presence of a shallow impermeable bedrock) and agriculture is mainly livestock/dairy farming with maize, temporary grasslands and winter cereals. SWAT has been chosen as one of the most commonly used and well supported water quality modeling systems available. It can be applied on medium to very large catchments, and the generation of input files is eased by GIS-based tools. It also has been calibrated and considered adequate on small catchments (Green and Van Griensven, 2008).

The TNT2 model was specifically designed to simulate soil-groundwater interactions (e.g. the distribution of denitrification and overland flow according to the extension dynamics of the saturated areas) to take into account spatial interactions within the catchment in a shallow aquifer context. It is process-based and spatially distributed (for detailed description see Beaujouan et al. (2002) and Oehler et al. (2009)). The hydrological model is based on some of TOPMODEL hypotheses (Beven, 1997). The crop growth and N biotransformation are simulated using STICS generic crop model (Brisson et al., 1998; Brisson et al., 2002). The catchment is discretized in a set of columns, each column corresponding to one cell of a regular digital elevation model grid. The soil parameters, the agriculture management data and the climate data are distributed using the same grid (raster maps). The agriculture management information required is: sowing (date and crop type), fertilization (date and amount) and harvesting (date and residue management).

The model SWAT (Santhi et al., 2001; Van Griensven and Bauwens, 2003; Borah and Bera, 2004; Ramanaravanan et al., 2005; Arnold and Allen, 1996) is a process based model and was designed to assess the long term impact of land management on water balance, sediment transport and non-point source pollution in large river basins. It has been used and assessed in many studies in the world for N transfer, mainly in large catchments (e.g. as in Grizzetti et al. (2003), Santhi et al. (2006), Abbaspour et al.

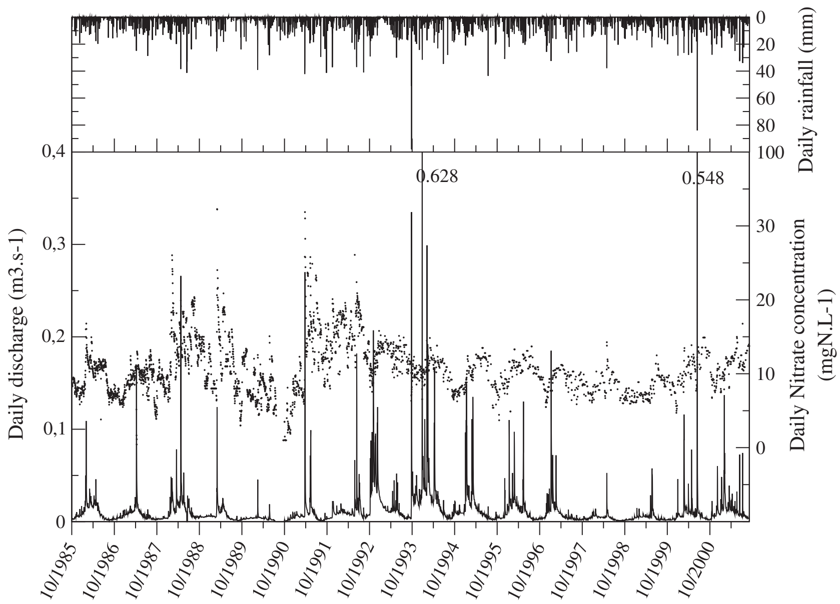

Fig. 2. Daily discharge (m^3 s^{-1}), rainfall (mm), N concentration (mg, N—NO_3^- L^{-1}) measured in Montoussé river, at the outlet of auradé basin. *source*: GPN-Total.

(2007), Pohlert et al. (2007b), Pohlert et al. (2007a), Bouraoui and Grizzetti (2008)) but also in small ones (e.g. as in Green and Van Griensven (2008)). The spatial unit is the sub-catchment that is further divided into hydrologic response units (HRUs) (Neitsch et al., 2002), a sub-unit defined by overlaying soils, land use and slope maps. Most soil and aquifer computing is done at the HRU scale and results are integrated at the sub-basin scale. The soil and crop model is mainly based on EPIC (Williams et al., 1984). Sowing, fertilization, tillage and harvesting informations can be input at the agricultural field scale.

2.5.2. Model comparison

Both models are based on comparable soil and crop models. The main similarity is the plant growth model. A potential yield is calculated with global radiation input and a water stress factor is computed to limit this potential growth. The water evaporation is based on Penman–Monteith potential evapotranspiration limited by the evaluation of the Leaf Area Index. The differences between both models are summarized in Table 3 and will be confronted regarding simulation results. SWAT uses the Curve Number method (USDA-SCS, 1972) to simulate runoff, TNT2 simulates runoff on saturated zones. Soil water and N transfer is based on the capacitive conceptual model of Burns (Burns, 1974) in TNT2 and on a capacitive linear model in SWAT. Aquifer flows computation is based on a topographic gradient in TNT2 calculated for each cell. The hydraulic gradient in each cell is constant and controlled by topography, and the hydraulic conductivity decreases exponentially with depth. The model parameters *T*0 (lateral transmissivity in m^2 per day) and *m* (exponential decay factor of the hydraulic conductivity with depth in m). Aquifer flows computation is based on a hydrological gradient in SWAT, depending on water table and a base-flow recession constant defined for each sub-basin.

In TNT2, the humus mineralization rate depends on soil active organic matter, texture, humidity and soil temperature. The model includes three compartments: the residues, microbial biomass and humified organic matter. Seven parameters are used to describe the C and N fluxes. The decomposed C is either mineralized as CO_2 or assimilated by the soil microflora, microbial decay producing both C humification and secondary C mineralization. The N dynamics are governed by the C rates and the C:N ratio of the compartments which remain constant in the absence of nitrogen

Table 3
Conceptual differences between SWAT and TNT2 used in this study.

	TNT2	SWAT
Runoff evaluation	Saturated zone Hortonian coefficient	Curve Number and cracking
Soil transfer	Burns model	exponential reservoir drainage
Groundwater	Derived from TopModel	Hydrological gradient
Mineralization	STICS	PAPRAN
Denitrification	NEMIS	Water content threshold user defined intensity rate
Spatialisation	Fully-distributed No river simulated	Semi-distributed Variable storage routing method

limitation. When new organic material is added (crop residues, manure, etc.), the decomposition depends on the C:N ratio of the material and of parameters controlling the growth and decay of the microbial decomposers (Nicolardot et al., 2001).

Two sources are considered for mineralization in SWAT: the fresh organic pool, associated with crop residue and microbial biomass, and the active organic pool associated with humus. The mineralization from humus is a fraction of humus depending on a rate coefficient defined by the user, a nutrient cycling temperature factor and a nutrient cycling water factor computed with the temperature and water content of each soil layer. The mineralization from fresh organic pool is a fraction of this pool depending on a decay rate constant: this rate is computed with a rate coefficient for mineralization of the residue defined by the user and three nutrient cycling residue composition/temperature/water factor. The nutrient cycling residue composition factor is function of C:N ratio of the residue pool: the more high the C:N ratio is, the smaller the decay rate constant is. The fraction of the nitrogen mineralized from the residue is so limited, but will be dependent on the amount of added fresh material.

Denitrification is simulated by a modified NEMIS approach (Hénault, 1995; Oehler et al., 2009) in TNT2: a potential denitrification rate is modulated by temperature, humidity, nitrate concentration and water residence time. This type of model has to be calibrated on field data to adjust the corrective function of these parameters. SWAT simulate denitrification as a function of amount of nitrate and carbon in soil layer and temperature of soil layer. The user defines a threshold of water content for denitrification to occur and a rate coefficient to control amount (or intensity) of denitrification. As the process is not well known, the amount of nitrogen loss by denitrification will be controlled and calibrated to be the same in both model.

The main difference between SWAT and TNT2 is in the spatial discretisation. TNT2 uses a regular cell grid scheme (distributed model): the cell-to-cell drainage routing is derived from the DTM analysis using a multidirectional scheme down to the stream network; the in-stream routing and processes are not simulated. SWAT uses the subcatchment as the spatial unit, subdivided into Hydrological Response Units (HRU) for soil and aquifer processes, but which are not spatially referenced (semi-distributed model). SWAT simulates nutrient transformation in the stream, controlled by the in-stream water quality component of the model, adapted from QUAL2E (Brown and Barnwell, 1987). The resulting water, nutrient and sediment fluxes from each HRU are accumulated within their corresponding sub-basin and allocated to the main reach of the sub-basin. Discharge and matter fluxes are routed within the stream network from one sub-basin to another and finally to the outlet of the catchment using either the variable storage routing method (Arnold and Allen, 1996) or the Muskingum river routing method.

2.6. Input data and calibration

To make the comparison valid, it was necessary to have the same input in both models. Fig. 3 illustrates the differences in taking spatial variables into account. Spatial input data are: agricultural plot map, soil map and a digital elevation model (DEM) with 5-m resolution. The DEM is used in SWAT to delineate a number of sub-basins chosen by the user (21 sub-basins) and the location of the reach. Each sub-basin comprises HRUs defined by a soil/agricultural-plot/slope-class combination. Four slope classes are defined, 0–5%, 5–10%, 10–20% and more than 20%. For TNT2, the drainage graph is created using the same DEM. Stream cells are determined by a drainage area threshold: for the cells over this threshold the outflow is routed directly to the outlet. Each cell derived from the DEM cells is characterized by a soil type, a land use identifier and a hydrological gradient.

For each agricultural plot, the following information is given: plant sown, amount of fertilizer, and date of each cultural operation. For instance, 17 years of crop rotation are given in SWAT for each agricultural plot. No simplification has been made to keep all historical information, and 17 years of crop rotation are given for each agricultural plot. The same weather data are used, and the same soil and aquifer parameters are set when possible (for example reservoir volume, initial organic matter content).

In a first step, the calibration of the hydrology is made by tuning the main parameters controlling the annual water balance: *Curve Number* and *Ground Water Delay* (SWAT) and *To* and *M* (TNT2).

In a second step, water balance and N cycle are controlled at the agricultural plot scale (aggregation of modeling units to the agricultural plot scale). Mineralization, plant growth (Leaf Area Index), N uptake and N exported by crop harvest are compared between models and to observed data or expert knowledge. After checking the N cycle in agricultural plot and at the catchment scale, the capillarity rise has been activated in SWAT and TNT2 to sustain evapotranspiration and to simulate aquifer N transfer to soil, specially to sustain plant consumption in TNT2 (SWAT already enabling plants to take N directly in groundwater). We have calibrated the parameters controlling this water transfer from the shallow aquifer to the overlaying unsaturated zone to have the same amount of water mobilized by this process ($GW-REVAP$ and $REVAP-MN$ for SWAT,

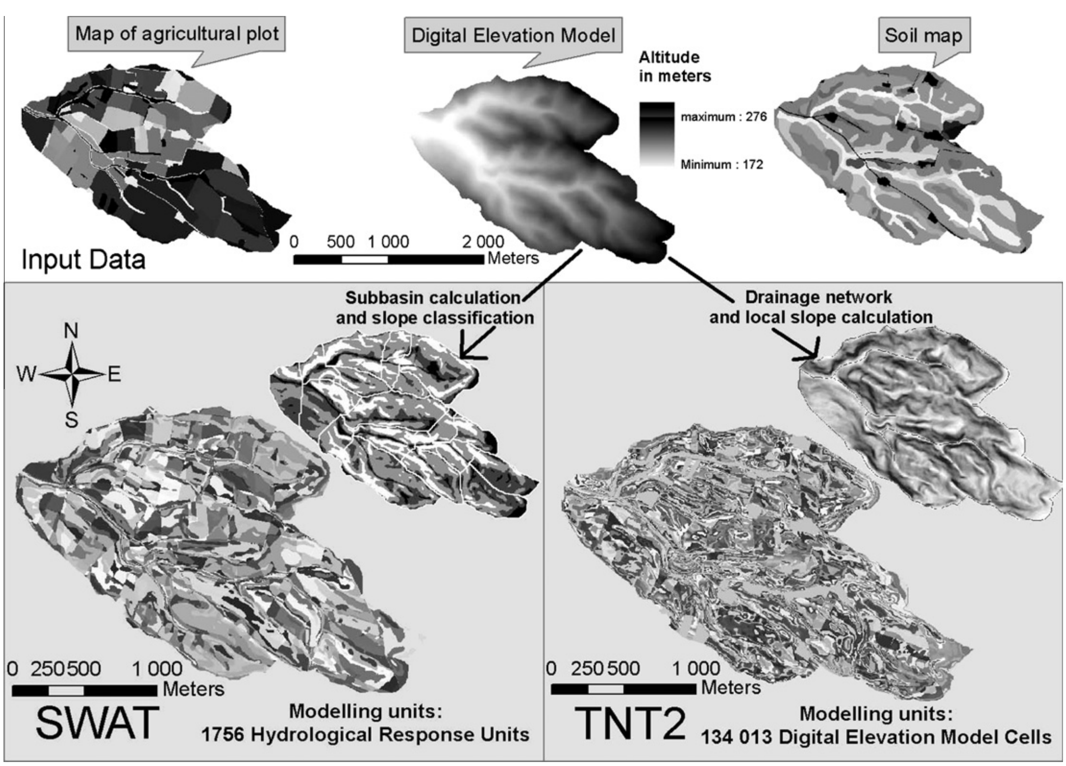

Fig. 3. Spatial data used in TNT2 and SWAT: soil map with 14 soil types (12 agricultural soil types, 1 for urban area and 1 for forest), DEM (5 × 5 m), agricultural plot map (92 agricultural plots). Integration of these data are detailed for fully distributed model TNT2 and semi-distributed model SWAT.

kRC and *expn* for TNT2). In the same way, mineralization and denitrification are calibrated to have equivalent annual fluxes in both models, the order of magnitude of these processes being validated by agronomic expertise. Simulations were performed at a daily time step for 17 years, from September 1985 to September 2001, the first 2 years (September 1985 to September 1987) being used to initialize the models, and not taken into account in calibration and results analysis. Nash-Sutcliffe's efficiency coefficient (Nash and Sutcliffe, 1970) and RMSE (Eq. (1)) are used as optimization criteria for daily discharge and N fluxes.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{T}} \tag{1}$$

where Q_o^t is observed discharge at the time t, Q_m^t is modeled discharge at the time t. It is expressed as a percentage, where lower values indicate less residual variance. Computing time for each model is quite different: a 17 year run takes 10 minutes for the 1756 modeling units (HRU) in SWAT and 12 h for the 134,013 modeling units (grid cells) in TNT2.

3. Results

3.1. Hydrology of the catchment

Measured and simulated daily water discharge are presented in Fig. 4. The period from 1/10/1987 to 1/09/2001 has been used to calculate the Nash-Sutcliffe coefficients for both models. Acceptable performances were obtained, with $E = 0.6$ and $E = 0.5$, for SWAT and TNT2 respectively. Table 4 summarizes water and N balance simulated with both models. The calibration was focussed on reproducing yearly stream discharge (113 mm y^{-1}). Both models predicted a similar actual evapotranspiration from a same potential evaporation (1023 mm y^{-1}). TNT2 and SWAT simulate differently the main processes of water transfer in the catchment: TNT2 predicts more base-flow during winter and the beginning of spring whereas SWAT predicts more overland flow and rapid transfer, which is, most of time, more realistic. Fig. 5 shows the ability of TNT2 to simulate small variations in low flow period, with small peaks of runoff due to contribution of the saturated areas. The winter 1996–1997 discharge is overestimated by both models (see also Fig. 6).

3.2. Apportionment of N fluxes

Table 4 gives the magnitude of each main processes of production and consumption of mineral N in the catchment. Plant uptake and crop yield are comparable to observed range of possible values. The amount of mineral fertilizer applied is not exactly the same (94 and 98 kg N ha^{-1} y^{-1} for TNT2 and SWAT respectively) because TNT2 simulates some volatilization of NH_3 for each application (equivalent to 2 kg N ha^{-1} y^{-1}). Furthermore, fertilizer are input as amount of fertilizer types in SWAT while it is given in mineral N in the agricultural database which could explain the remaining difference between amount of mineral fertilizer applied in models. Mineralization and denitrification processes have been calibrated to be close in both models, with 67 and 65 kg N ha^{-1} y^{-1} of mineralization, 26 and 25 kg N ha^{-1} y^{-1} of denitrification for TNT2 and SWAT respectively. Differences between simulated and observed stream loads are within the range of measurement errors.

The annual observed mean N losses in river is estimated to be of 13.31 kg N ha^{-1} y^{-1}. The Fig. 7 presents the annual agricultural yield for each major crop of the study period. TNT2 tends to make a systematic overestimation of yields for durum and bread winter wheat, whereas it under-estimates sunflower yields. Swat simulates accurately Durum wheat yields and the inter-annual variations for the period from 1994 to 2000. Bread wheat yields are underestimated by SWAT although the same crop parameters as for the Durum wheat are used. The only difference between bread wheat and durum wheat is the average amount of fertiliser inputs, which is higher for durum wheat. SWAT overestimates systematically sunflower yields. All these results give an overview of crop growth and biomass production simulated by the two models. The inter-annual variability is well simulated and coherent between models. The simulated N uptake by plant is close in the two models. Yields are maybe overestimated in TNT2 because of a bad estimation of the part of seed production in total biomass and also because the possible impact of pests are not simulated.

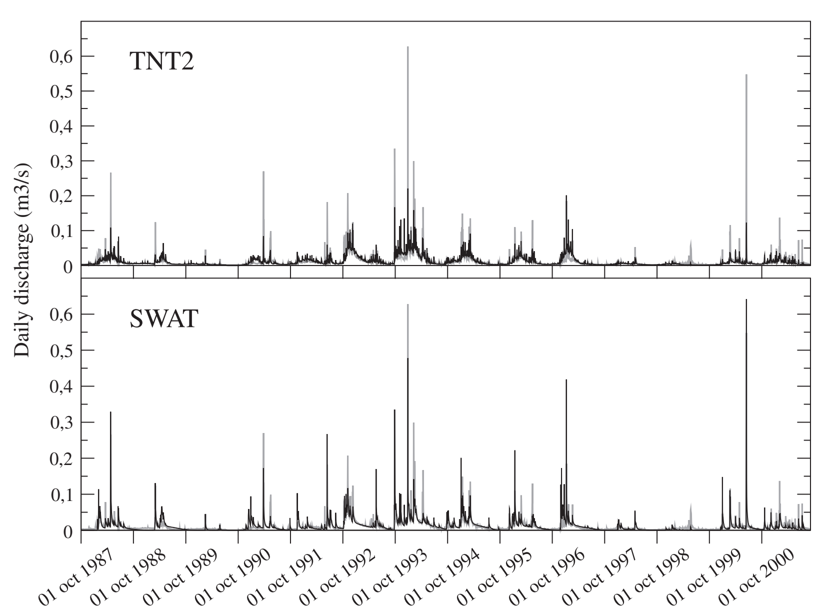

Fig. 4. Daily discharge (m^3 s^{-1}) observed (gray line) and simulated (black line) with semi-distributed model SWAT and fully distributed model TNT2 at the outlet of Auradé. Nash-Sutcliffe coefficient is 0.5 and 0.6 for respectively TNT2 and SWAT simulations.

Table 4
Yearly water and N balance simulated in models, from 1987 to 2001.

In/out	Water budget, mm y^{-1}	TNT2	SWAT
Input	Rainfall	676	676
	Potential evapotranspiration	1020	1020
Output	Actual evapotranspiration	566	559
Output	Discharge	110	114
	δ stock	0	3
	N budget, kg N ha^{-1} y^{-1}		
Input	N in Rainfall	7	7
Input	Mineral fertilizer	96	98
Input	Mineralization	67	65
Output	Fertilizer volatilization	2	0
Output	Plant uptake	127	128
Output	Denitrification	26	25
Output	Stream losses	13.15	12.88
	δ stock	1.5	4

3.3. Spatial and temporal variation of mineralization and denitrification

Results of temporal variability are shown in Fig. 8. A negative mineralization indicates immobilization. The mineralization dynamics are simulated differently: SWAT simulates a continuous humus mineralization with an increase when straws are buried and a decrease afterwards. TNT2 simulates more marked seasonal variations with a net increase of mineralization after summer. Each burying of straws induces immobilization, due to the building up of the soil microbial biomass and because of the low C:N ratio of the straw. This exhausts temporarily the mineral N content of the soil and slow down the mineralization, that begin again to increase with the soil wetting in autumn. There is an inter-annual variability of mineralization. The Fig. 9 shows that TNT2 predicts more mineralization than SWAT during the first period of simulation (from 1987 to 1991) and less in the last years (from 1997 to 2001), for a comparable mean annual mineralization on the whole study period. The basic assumptions of each model described previously are quite different for this process as TNT2 is simulating a microbial biomass growth, and SWAT is only using organic matter ratio. It is leading to these differences in temporal results. In both models, mineralization and denitrification are linked in time since denitrification is dependant on available NO_3^- in soil which is often limiting due to plant uptake and leaching.

Denitrification dynamics are simulated differently as well. According to TNT2, denitrification occurs mainly in autumn with TNT2, when mineralization is maximal and plant uptake minimal. In SWAT, denitrification occurs mainly during the months after the burying of straws, and high denitrification rates are occuring in winter. In both models, the most limiting factors are N and soil water saturation.

The spatial distribution of mean annual net mineralization and denitrification is presented in Fig. 10. The amount of net denitrification (panel a) and mineralization (panel b) has been calculated for each modeling units (HRU and cell for SWAT and TNT2 respectively). As expected, the two models simulate different spatial patterns of mineralization and denitrification. The impact of soil and land use on the amount of yearly net mineralization are clear. The soil characteristics and the agricultural practices explain the major variability of both processes. The roads and the forests show the lowest rates in both models, differences lying in the distribution of the highest rates of mineralization and denitrification area.

In SWAT, the mineralization and denitrification rates result directly from the combination of soil type and land use. The highest mineralization rates are found in soils with high amount of crop residue, resulting from a cultural succession of canola and winter wheat. High denitrifying areas are corresponding to deeper soils with higher total organic matter content and total water storage.

In TNT2, mineralization and denitrification processes are mainly controlled by soil water content. However, the mineralization and denitrification rates are lower in the bottom of slopes in general, even is these are the most saturated areas. Low denitrification rates could be explained by:

- low nitrate levels: the land cover is in a majority tree strips and small forests, with no fertilization and low mineralization rates predicted because of the high C:N ratio of soil organic matter,
- saturated area dynamics: they are confined to ditches and they are saturated mainly in winter (low temperatures), and flows may be too fast (residence time $\ll$5 days).

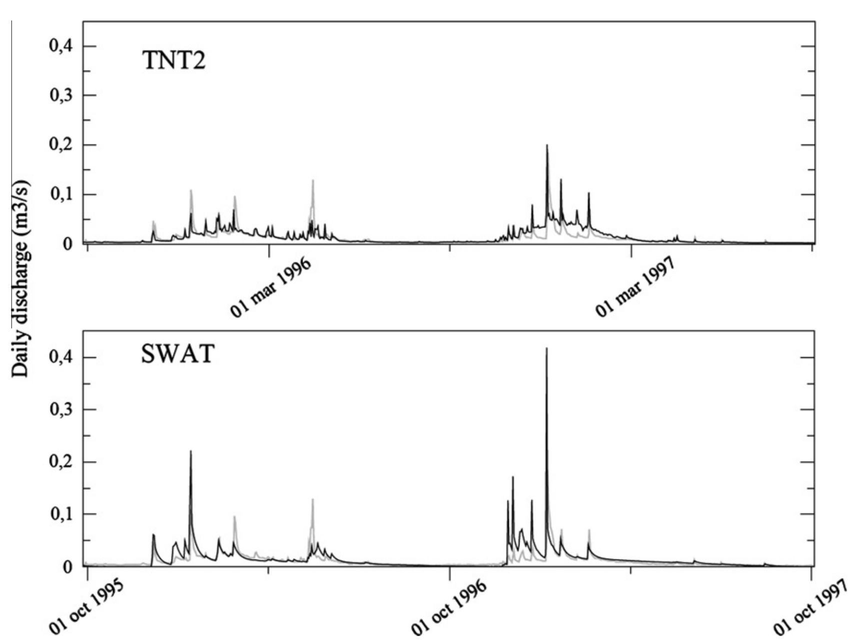

Fig. 5. Daily discharge (m^3 s^{-1}) observed (gray line) and simulated (black line) with semi-distributed model SWAT and fully distributed model TNT2 at the outlet of Auradé from October 1995 to October 1997.

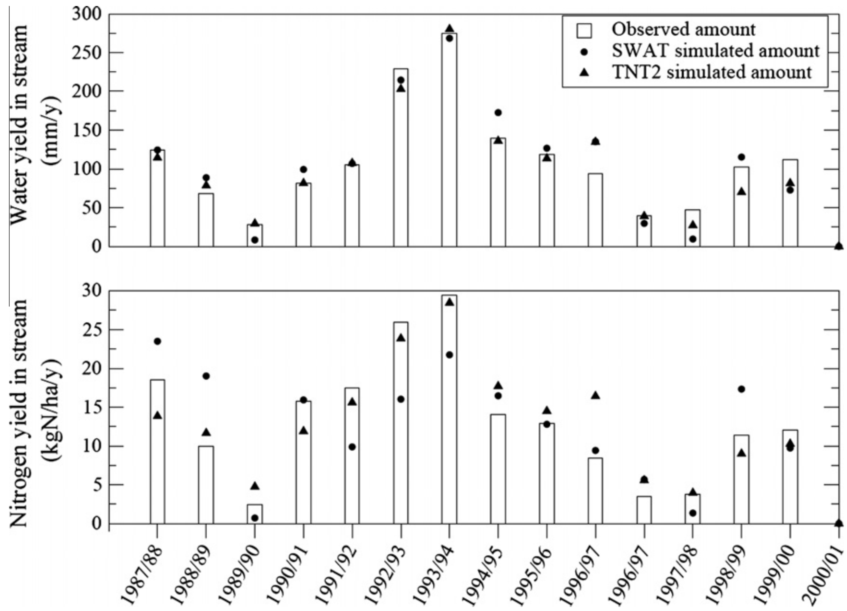

Fig. 6. Annual discharge and N loads (mm and kg N) observed and simulated with semi-distributed model SWAT and fully distributed model TNT2 at the outlet of Auradé from year 1987–1988 to year 2000–2001. RMSE of annual discharge are 0.018 and 0.022 mm for respectively TNT2 and SWAT. RMSE for annual load are 78.6 and 65 kg N for respectively TNT2 and SWAT.

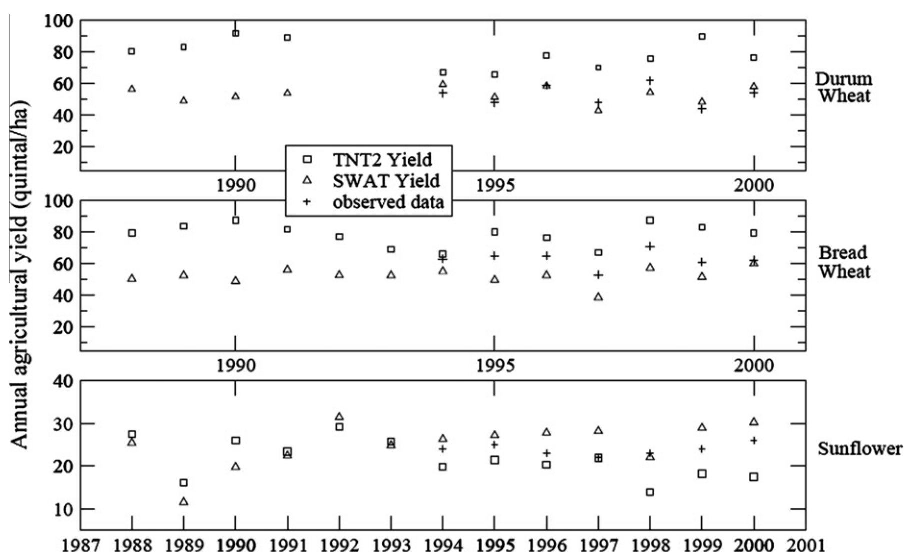

Fig. 7. Annual average agricultural yield for the three major plant sowed simulated with TNT2 and SWAT from 1988 to 2000 in Auradé catchment. Measured yield are reported since 1994.

3.4. N loads in stream

Simulated N loads are presented in Fig. 11. Both models performed poorly in simulating daily loads, with a Nash–Sutcliffe coefficient of 0.15 for SWAT and 0.25 for TNT2. The RMSE were, for SWAT and TNT2, 32.2 and 28.3 kg day^{-1}. The daily simulated nitrogen loads are poorly correlated to observed datas (around 0.4 for both models). The correlation coefficient between simulated and observed monthly loads is about 0.65 for SWAT and 0.74 for TNT2 simulation. The increase of correlation taking monthly loads is more important with TNT2 than SWAT, this model simulates better monthly loads (r means and standard errors evaluated by a jackknife method, student test, $p \ll 0.05$). Intensive daily nitrogen loads corresponding to rainfall events are not simulated with TNT2, and not enough intense with SWAT. The study period presents a wide range of climatic events: either very dry spells or very intense flood events, representative of regional climatic conditions. Fig. 6 shows the measured and simulated water and N yearly yields. TNT2 and SWAT simulate well general trends and interannual variations except for the 1996–1997 year, where both models overestimate the loads. The discharge during dry years is well simulated in TNT2 (1989–1990 and 1996–1997) while SWAT underestimates water yield. In 1997–1998, both models underestimate the low water yield observed. During humid years, both models simulate the right water yields e.g. from 1991–1992 to 1993–1994. N loads are better simulated for the three most humid

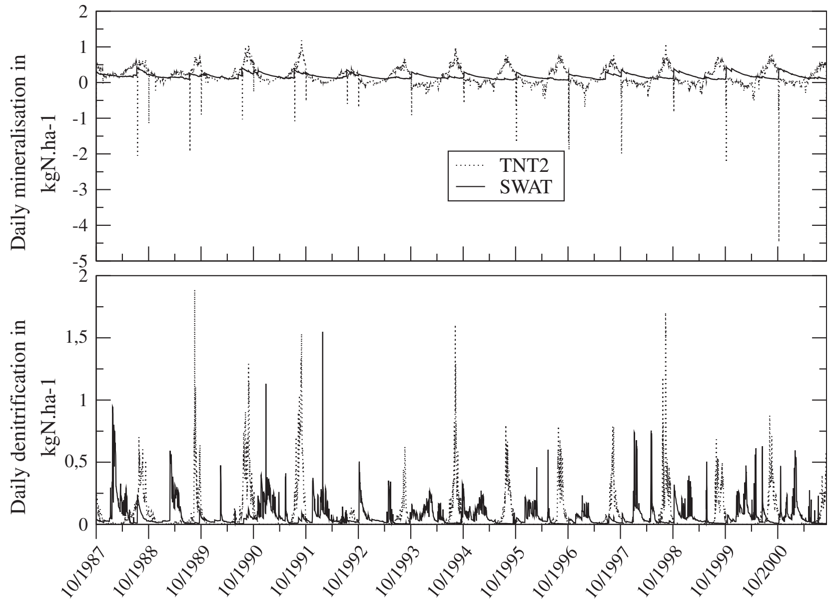

Fig. 8. Daily net mineralization (figure on the top) and denitrification (figure below) simulated with SWAT (gray line) and TNT2 (black line) during the study period (from 01/10/1987 to 01/09/2001). Values are given as the daily mean for the Auradé catchment in kg N.ha^{-1}.day^{-1}.

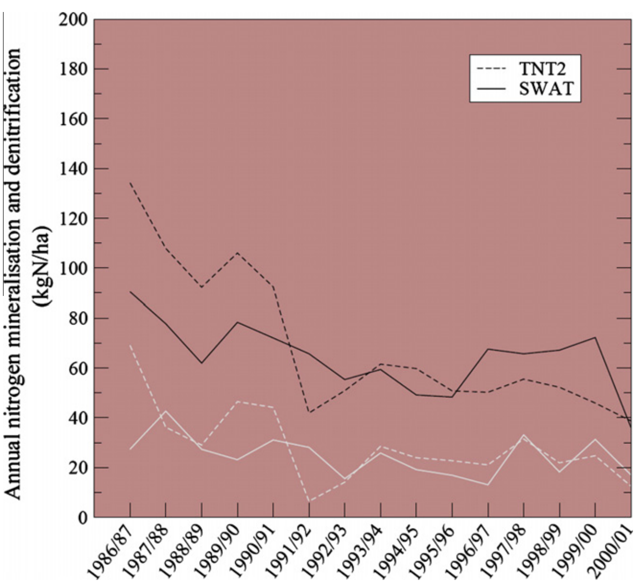

Fig. 9. Annual amount of mineralization (black line) and denitrification (white line) simulated with SWAT (full line) and TNT2 (dotted line) during the study period (from 1987 to 2001). Values are given as the annual amount for the Auradé catchment in kg N ha^{-1}.

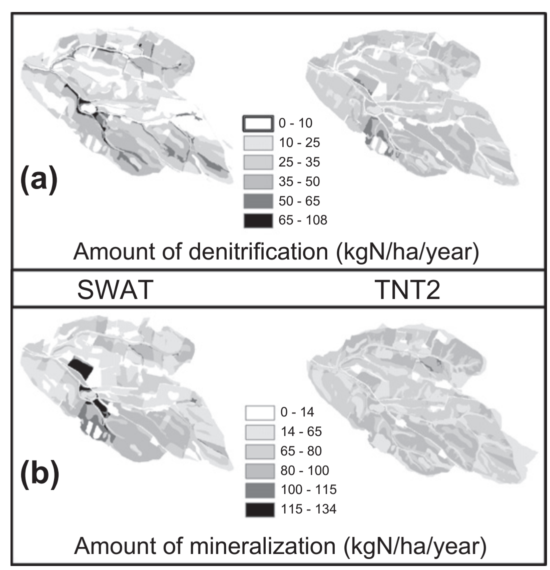

Fig. 10. Yearly denitrification (a), mineralization (b) with SWAT (left) and TNT2 (right) during the study period (from 01/10/1987 to 01/09/2001). Values are given for each modeling units (HRU and cell for respectively SWAT and TNT2) as the mean of the yearly denitrification and mineralization (a) and (b) modeled for the Auradé catchment in kg N ha^{-1} day^{-1}.

years with TNT2, SWAT systematically underestimating N loads. During dry years, SWAT underestimate nitrate outputs because it underestimates water discharge.

Dynamics of daily N fluxes are simulated differently (Fig. 11): SWAT simulates intense peaks of N load (maximum of 267 kg N day^{-1}) during small periods of 20 days; TNT2 simulates similar daily loads along the year. The dynamics of N loads in low flow periods are well reproduced by both model, when mainly driven by aquifer supply.

Cumulative flows and N loads are presented in Fig. 12. Cumulative flows are really close between both models and to the measures. Measured cumulative N loads have a sigmoid-like shape. Three periods can be outlined: the first period with a small cumulative slope, which is well simulated by TNT2 and with overestimations by SWAT (1987–1991); the second (the inflection) period where slope increases (from 1992 to 1996) and when cumulative TNT2 loads are going over the SWAT cumulative curve; a third period from 1997 to 2000 with a slope equivalent to the first period and where TNT2 overestimate N loads. Inter annual variability of N losses in river seems to be better simulated with TNT2.

3.5. N concentration in the stream

Fig. 13 presents the daily concentration simulated by the two models and compared to calculated concentrations based on measurements. The measurements are reflecting a high variability, at

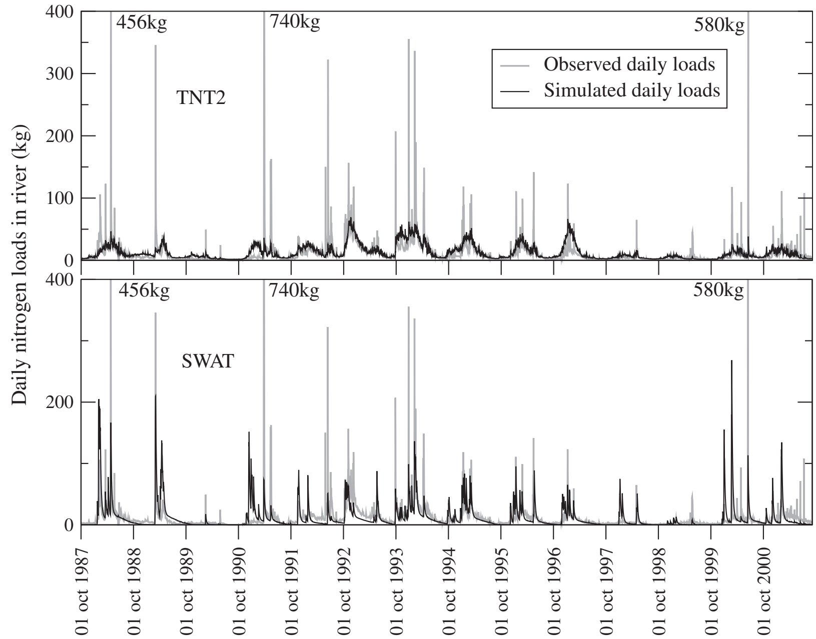

Fig. 11. Daily N loads in river (kg day^{-1}) observed (gray line) and simulated (black line) with semi-distributed model SWAT and fully distributed model TNT2 at the outlet of Auradé.

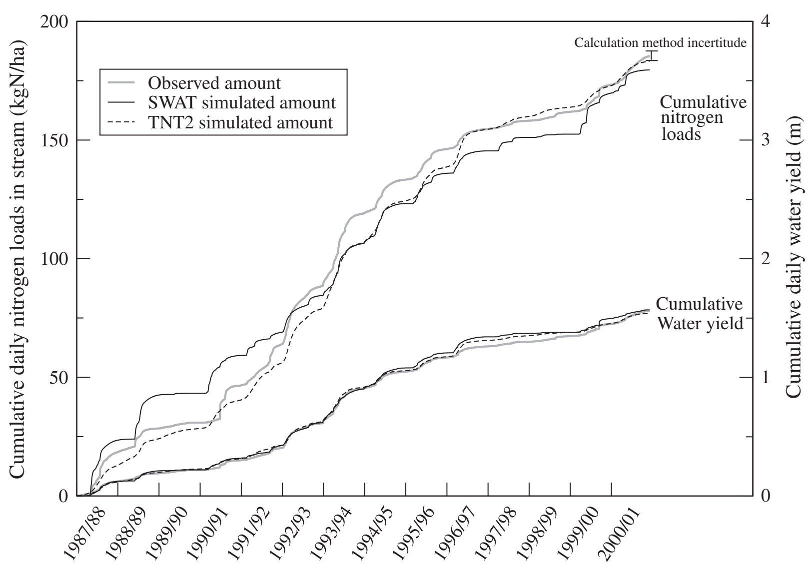

Fig. 12. Cumulative daily water discharge and N loads observed and simulated at the outlet of the Auradé catchment, simulated by SWAT (full line) and TNT2 (dotted line) from 01/10/1987 to 01/09/2001. Discharge are given in m and N loads in kg N ha^{-1}.

different time scale: infra-daily during flood events, a marked seasonality and yearly variability. Both models have difficulties to simulate accurately daily concentrations. TNT2 systematically simulates a decrease during flood events and an increase during dry period, the opposite of what is observed (e.g. during summer 1990). TNT2 globally overestimates concentrations during the last years, maybe as an effect of underestimating water yield (see Fig. 6). Overall, N loads are well simulated because concentrations are counterbalanced by water yields.

SWAT is predicting a wider range of concentrations with especially extreme daily concentrations during major flood events (e.g. beginning of year 1988 and 1989). Concentrations are highly variable for the last years of simulation when aquifers water storage is low. Indeed, the water yields for years 1996–1998 are underestimated (see Fig. 6). From 1991 to 1994, concentrations as well as the annual N loads are underestimated by SWAT whereas the range of concentration simulated by TNT2 corresponds to observed values.

4. Discussion

4.1. Water discharge and N loads to the stream

We wanted to take into account the highly contrasted humid and dry years. As we did not need to have a strong evaluation of the generalization of the models (e.g. for forecasting), the calibration was carried out on the whole study period (i.e. without valida-

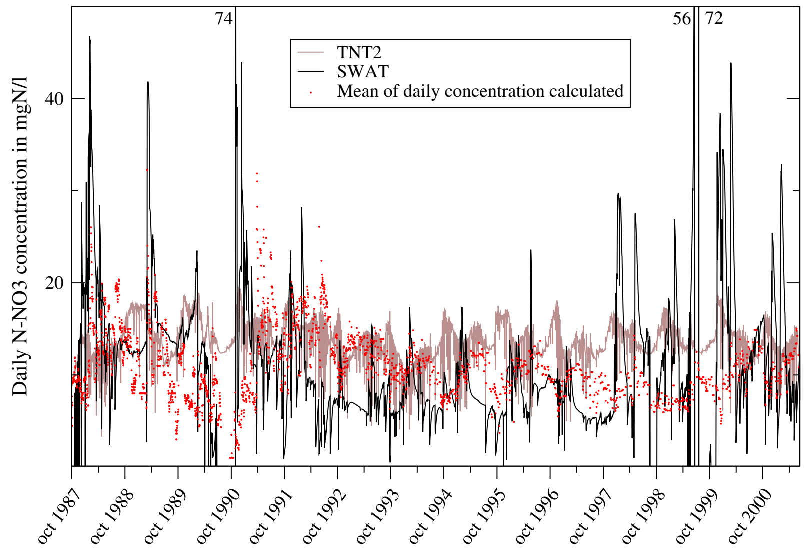

Fig. 13. Simulated and mean of daily concentration calculated from observed data during the study period (from October 1987 to September 2001). Mean daily concentration has been calculated from measured concentration for 2834 days of the 5814 days studied.

tion). To illustrate some of the issues of the calibration/validation in this highly contrasted period, which asks for longer time series to capture the catchment behavior, we computed Nash coefficients for the first half and the second half of the studied period. Confidence intervals were also computed (95%, bootstrap). The Nash coefficients and confidence intervals were, for TNT2 and SWAT (min and max in parenthesis), 0.48 (0.40–0.59) and 0.61 (0.44–0.89) for the first half of the simulation period; 0.48 (0.39–0.57) and 0.48 (0.22–0.92) for the second half. Confidence intervals are quite wide, especially for the more 'problematic' second period. Choosing a 'representative' period for validation can be tricky and we could quickly see the possible strong bias of a 'wise' choice. Again, these results suggested that the response of TNT2 was more stable than SWAT. The water balance and daily flow are considered acceptable in both cases, bearing in mind that the hydrological response time is short and would have required a finer time step to be modeled more accurately. Using a disaggregating method for the rainfall/PET and a sub-daily hydrological model might have been an option (e.g. like in Topnet (Bandaragoda et al., 2004), also based on Topmodel), if we had high quality sub-daily flow measurements, which was not the case. Looking at Fig. 4 in particular, we can see that the weaknesses of the models are different: TNT2 simulate accurately humid years (e.g. 1992–1993) and overland flow on saturated soil area generated by low rainfalls. It fails to simulate overland flow in every case of intense rainfall events, due to the simplistic hortonian flow module. The curve number modeling approach of SWAT performs better at simulating the quick flows during these events, although the result is far from perfect. On top of the time step issue mentioned above, soil surface condition is another incertitude. SWAT simulates cracking in summer that avoid overland flow to be wrongly simulated during dry period. The results of cracking process activation in SWAT are coherent with observations, but the surface condition is only partially taken into account with Curve Number approach in SWAT. TNT2 has no procedure for changing what triggers surface infiltration.

The differences of simulated water flow dynamics partly explain the differences in the dynamics of N loads. The amount of overland flow simulated in TNT2 is less than in SWAT and is generated on saturated soil area only. This results in a higher infiltration on arable soils in TNT2, and more leaching if nitrate is available. The Fig. 14 shows simulated N storage and water volume in the aquifer. More water and N are transferred to the aquifer in TNT2 than in SWAT. Stream concentration is therefore simulated differently: SWAT simulates more rapid N transfer in lateral flow and TNT2 simulates more leaching and groundwater contribution to stream. Fig. 13 shows that peaks of concentration simulated with SWAT are generally overestimated compared to observed data, while flow peaks are generally underestimated (see Fig. 4).

TNT2 simulates more accurately recurring humid years (e.g. 1992–1994) in terms of discharge, concentration and therefore N loads, because the water infiltration and the aquifer contribution to stream are dominant during those years. This suggests that one major reason why both models perform poorly in this context is because the hydrodynamic properties of the clay-ish material are highly variable, depending on the frequency and timing of drying and wetting periods. Overall, the dominance of surface runoff, with its dynamics apparently influenced by the state of the clay-ish material (soil cracking and preferential flow path), is the key issue in this case. Although the seasonal and annual nitrogen dynamic is relatively well reproduced, improvement of the modeling of fast transfers during flash-flood events will be necessary to improve daily fluxes and concentrations.

We know that a part of soil nitrogen could be quickly transferred by runoff during these flashy flood events (especially nitrate). The daily nitrogen losses are high during these events. TNT2 was not able to simulate these events, and the nitrogen leached into the aquifer instead, as shown in Fig. 13. SWAT was also missing some of these events and underestimates N losses. No attenuation of nitrogen in the aquifers is modeled in SWAT and TNT2 (which nevertheless may be low as the water residence time is short (<1 year)). Hence the global N budget was still balanced at a seasonal time scale, even if leaching was overestimated.

The use of the two models may have shed some light on the input data uncertainties, especially because of a relative long period modeling. For example, the water flow of the year 1996–1997 is strongly overestimated in both models. This leads to suspect a bias in the rainfall data measurements or potential evapotranspiration during this year, and this could also apply to other shorter periods of the study. Furthermore, the *in situ* sampling protocol of concentration was not consistent over time: the first part of the period (1987–1989) has been sampled with a high frequency (more than 1000 measurements in a year), the second part has been sampled with a lower frequency (more than 400 sample in a year from

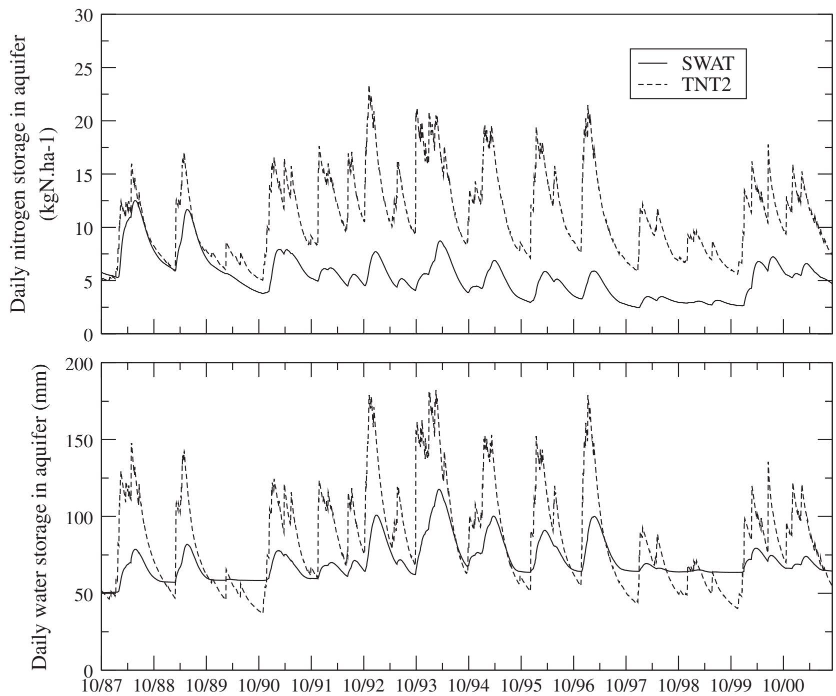

Fig. 14. Daily water and N storage in aquifer simulated by SWAT (full line) and TNT2 (dotted line) from 01/10/1987 to 01/09/2001. Values are given in mm and kg N ha^{-1} for respectively water and N storage.

1990 to 1994) and the third part has been somehow insufficiently sampled to represent well the daily concentration dynamic (less than 200 samples per year from 1995 to 2001). It could partly explain the high variability of computed daily concentration for the first and second period (that are dry and humid), and less variable concentrations in the third period.

4.2. Nitrogen budget at the catchment scale

The spatial dynamics of mineralization and denitrification rates have an impact on N leaching from soil. In TNT2, the maximum of mineralization and denitrification rates occur during the end of summer and the beginning of autumn (Fig. 8). The nitrate available for leaching is only what is left after denitrification. On the contrary, SWAT simulates a less variable mineralization, with a maximum at the harvest date, decreasing then from this maximum to a minimum a year later. This mainly corresponds to the mineralization of straws. There is an excess of soil nitrate in winter, which is partly denitrified, and partly leached. The plant uptake is not in competition with the denitrification process during the plant growth period, because denitrification occurs at the beginning of summer in TNT2, when temperature is high, and in winter in SWAT, with wet conditions and a nitrate supply from mineralization. The Fig. 10 shows that denitrification hot spots are not localized in the same areas. The highest denitrification rates in SWAT correspond to the deeper soils in the valley bottom and in some agricultural plots where the amount of mineralization is equivalent to amount of denitrification. The highest denitrification rates in TNT2 correspond to pothole areas inside agricultural plots, where water level and residence time is high. Although the models simulate the same annual loads, they differ strongly in time and space distribution of the processes. Denitrification fluxes need to be compared with the flux balance of both N mineralization and N fertilization: the fraction of denitrification is about 17% and 15% of the total nitrogen input to the soil for TNT2 and SWAT. In reality, saturated areas are located in bottom part, close to the stream (riparian area) and some perched water table are sustaining discharge in summer. TNT2 is indeed simulating a very small saturated zone along the stream, where water and nitrogen coming from the slopes does not stay for long, which limits effective denitrification. Indeed, no zones have been clearly identified as a sink of nitrogen by denitrification due to high water levels. The relatively high rates of denitrification modeled are found in the fields with high fertilization rates and soils with high clay content, which is coherent with literature. However, further work is needed to assess denitrification rates in such context. In the meantime, more generalized denitrification models could be used, notably based on soil organic matter content (Oehler et al., 2010), as it may be a strong limiting factor on this site.

4.3. About trends

Both models simulate well inter-annual trends that are contrasted for this relatively long period. TNT2 predicts accurately annual N loads. SWAT is able to simulate more rapid transfer of nitrogen to the stream, due to a better account overland and lateral shallow flow. The peaks of nitrogen during flood events simulated with SWAT correspond to observed phenomena, even if they are often underestimated.

This study site does not function as most temperate agricultural catchments. Stream loads account for 1–12% of total output per year. N losses are relatively low for a small intense agricultural catchment, with 13 kg N ha^{-1} y^{-1} only. Probst (1985) has estimated the same value (13.8 kg N ha^{-1} y^{-1}) for the Girou river basin (520 km^2) which is a tributary of the Garonne river flowing on the same molassic substrate. Kattan et al. (1986) estimated 10.7 kg N ha^{-1} y^{-1} for the Mosel river basin (6847 km^2) in North Eastern France of which 60% are cultivated. Gascuel-Odoux et al. (2010) report 25–100 kg N ha^{-1} y^{-1} for catchments in Brittany (France), and a recent review of N fluxes from European catchments indicates that sites with more than 80% of their land-use being farmland lose between 20 and 120 kg ha^{-1} in average (Billen et al., 2009). The smaller this load is, the higher uncertainties in modeling are. The hydrological control is high for infra annual dynamics of N loads. The Fig. 12 shows that, even with a close estimation of cumulative water discharge between the two models, TNT2 and SWAT simulate differently seasonnal and interannual variation of N loads in the stream. As seen before, monthly loads are better simulated with TNT2. Since agricultural yields have the same interannual variations in both models, we suppose that the interannual variability of mineralization explains the better performance of TNT2 (see Fig. 9). This suggests that the processes controlling the N available for leaching are better simulated in TNT2.

5. Conclusion

This work can be seen as an illustration of the uncertainities of using agro-hydrological models to simulate catchment water chemistry, even if the models are widely used and tested, and if the catchment is well monitored. It also illustrates the problem what can be called 'equifinality' (Beven, 1993; Beven and Freer, 2001), i.e. different model structures can reproduce outlet flows and loads with different internal dynamics, although we have strived to constraint the calibration (i.e, fixing similar mean loads of mineralization and denitrification). Free and independent calibrations of the two models would surely have led to more contrasted conclusions.

Results show that with a large enough measurement dataset, in particular with a detailed agricultural practice information and with long enough time series of hydrological and hydrochemical data for calibrating the models, simulations give reasonable estimations of the water and N fluxes at the outlet. For both models, water yield is accurately reproduced. The simulations highlight the poor prediction of flood events with daily timestep models. The studied catchment is highly responsive to rain events and the curve number approach used in SWAT is more efficient than the variable source area approach used in TNT2. TNT2 performs better than SWAT in simulating base flow. SWAT simulates more infiltration, TNT2 simulates more leaching, more N transfers through the aquifer and less overland flow. This partly explained the differences in the simulated stream nitrate concentration. Because even if simulated annual water and N yields are very close, major differences were found regarding mineralization and denitrification dynamics.

Climatic control on N processes seems simulated better in TNT2 thanks to the more detailed STICS approach. These results confirm that the use of such tools for prediction must be considered with care, unless a proper calibration and validation of the major N processes is carried out. There may be a need to either refine mineralization and denitrification modeling (e.g. using an event based approach like in DNDC (Li et al., 1992)) or use more generalized simplified approaches (e.g. as in Oehler et al. (2010) for the denitrification model). Spatially distributed measurements of mineralization dynamics in soil as well as denitrification would help to evaluate the realism of the different modeling approaches.

Acknowledgments

We would like to thank the 'Association des Agriculteurs d'Auradé, Pierrette Gouaux from the CESBIO (CNRS-CNES-IRD-Université de Toulouse), Hervé Squividant and Pierre Moreau from SAS (INRA Rennes) for their cooperation. Nitrate concentration and stream discharge were recorded within the framework of a GPN-ECOLAB convention on the experimental catchment of Auradé. This research was carried out within the IMAQUE Project supported by regional (CPER) and European (FEDER) funds and within INSOLEVIE Inter-regional project funded by the Aquitaine and Midi-Pyrénées regions. Sylvain Ferrant is the recipient of an AKKA Technology fellowship within the CIFRE convention.

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