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Modelling the effect of the spatial distribution of agricultural practices on nitrogen fluxes in rural catchments

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Abstract

An integrated, hydrology and nitrogen dynamics model was developed to study the spatial interactions between soil and groundwater that can affect the nitrogen delivery to streamwater in rural catchments. The hydrological model TNT is based on TOPMODEL hypotheses but is it fully distributed according to a regular square grid. A subsurface flow component was distinguished to account for the supply of groundwater and nitrate to downslope soils. The crop growth and nitrogen biotransformations were simulated using an existing generic crop model, STICS. Both models are process-based, but kept as simple as possible. The integrated model was applied to theoretical catchments to analyze the combined effects of geomorphology and crop distribution on the whole catchment nitrogen budget. The catchments differed both in the slope profile and in the pattern of water pathways. The results suggest that placing crops acting as nitrogen sinks downslope potentially polluting crops could reduce significantly the streamwater contamination by nitrate. This effect is the highest for catchments with parallel water pathways and a wide concave bottomland. Nitrogen uptake by sink crops was quantitatively more important than denitrification to reduce nitrogen output. It is concluded that this model, although still in development, may prove an interesting working tool to investigate the effect of the landscape structure on nutrient budgets in ecosystems.

Keywords: Distributed hydrological model; Crop model; Water pollution; Geomorphology; DEM; Buffer zone

1. Introduction

In intensive farmland regions, streamwater pollution by nitrate is due to excess organic and mineral nitrogen fertilization. Even with careful farming practices, it is probably incompatible to maintain an optimal and regular crop yield and to keep nitrogen losses under about 30 kg N ha^{-1} year^{-1} (Mariotti, 1997). This is especially true when the proportion of organic fertilization is high, or in oceanic regions where mild winters and highly organic soils promote high mineralization rates which vary according to climate conditions. Since this level of nitrogen loss is still sufficient to

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affect streamwater quality, other remediation measures, such as landscape management, must be considered.

Landscape management measures to control nitrogen contamination of surface waters include buffer zones preservation or restoration (Haycock et al., 1996; Martin and Reddy, 1997; Mérot et al., 1998), these 'buffer zones' being riparian wetlands, vegetated strips or hedgerows. Common sense and a few studies (e.g. Decroux et al., 1991) suggest that the location of the pollution 'source parcels' in the landscape, especially the distance to the watercourse, may affect the amount of pollutant reaching the stream. This is empirically integrated in the export coefficient approach (Johnes, 1996) and similar approaches (Skop and Sorensen, 1998). The processes involved depend on the water pathways prevailing in the catchments. In temperate areas with impervious bedrock, the groundwater table is often located within the soil or at the surface in the lower part of the hillslopes: subsurface saturated flow makes it possible for upslope contaminated water to 'irrigate' downslope soils. This allows nitrogen uptake by crops or riparian vegetation and denitrification in waterlogged areas. To what extent could such processes affect nitrogen losses from rural catchments? The experimental evidence at the catchment scale is very hard to obtain. It would require either truly 'comparable' catchments with different landscape patterns or catchments where the land use pattern could be drastically changed. A simpler approach is to use simulation models to compare different scenarios.

Many nitrogen simulation models have been developed in the past three decades, and some reviews and comparisons can be found in the literature (Addiscott and Wagenet, 1985; Vachaud et al., 1988; Kauark-Leite, 1990; Ball and Trudgill, 1995; Diekkrüger et al., 1995; Van Grinsven et al., 1995; Addiscott and Mirza, 1998). A lot of models (SOILN, WAVE, LEACHN, CREAMS, SLIM, ...) compute the nitrogen fluxes and transformations at the plot scale, assuming one dimensional, vertical transfer. These models have sometimes been used at the catchment scale, simply by aggregating the plot scale results (ANSWERS, AGNPS, ...). Such models are of little use here, since the key process to simulate is the spatial interaction between the different zones of the catchment. In order to take some spatial processes into account, Krysanova et al. (1998) have coupled plot scale models with hydrologic reservoirs, but the routing from upslope to downslope is averaged and not simulated explicitly. The global conceptual models, representing the catchment — or the subcatchments — as a homogenous entity, are not more adequate for this. In such models, the spatial interactions are accounted for implicitly, in the fitting of the model results to the whole catchment response, but the identification and the quantification of these interactions are difficult: this should require extensive data either from different catchments or from manipulated catchments. The adequate models to study these spatial interactions must be process-based and spatially distributed. More precisely, they must simulate fairly accurately subsurface lateral flow, nitrogen transformations in soil and plant nitrogen uptake. Complex, mechanistic models such as SHE (Abbott et al., 1986) could be used as the hydrological modelling basis for such models, coupled with crop growth and nitrogen transformation models. For example, the WAVE and DAISY models have been used together with SHE to simulate nitrogen dynamics in catchments (Christiaens and Feyen, 1997). A simpler approach was once reported, coupling the SLIM model with a distributed hydrological model (Cooper et al., 1994). None of these models were found readily operational and, following Addiscott and Wagenet (1985) and Beven (1996), the mechanistic approach was discarded because at the catchment scale, its great complexity does not warrant better performance or sounder theoretical basis.

The choice was made to build up a new model that would better match the requirements of the study objectives. Since the objective was not to develop new modelling concepts but to quickly have an operational tool, one decided to adapt and to put together existing modelling approaches, preferably reasonably simple ones. This paper describes the structure of this model and presents preliminary results, obtained from an application of the model to 'virtual' catchments, aimed at giving a first order of magnitude of the effect of spatial interactions on nitrogen losses.

2. Material and methods

2.1. Models

The simulation model is constituted of two models running separately but synchronized following the producer–consumer technique (Ben-Ari, 1982) and exchanging data at each time step. The first model is a distributed hydrological model called topography-based nitrogen transfer (TNT), and the second is a crop model, STICS (Brisson et al., 1998).

2.2. From TOPMODEL to TNT and coupling principles

Since its creation by Beven and Kirkby (1979), TOPMODEL has been widely developed and used (Beven, 1997). It simulates flows in small catchments on impermeable bedrock, in which subsurface flow and overland flow on variable contributing area predominate. It is assumed that the downslope flux can be described as a steady state, saturated Darcian flux driven by a uniform recharge rate to the water table. The effective hydraulic gradient is taken as constant and equal to the local surface slope and the hydraulic transmissivity depends on soil saturation deficit. TOPMODEL calculates water fluxes at the outlet and the mean saturation deficit of the whole catchment at each time step, and distributes the saturation deficit at each point of the watershed, depending on a topographic index.

To represent the different flow pathways and the heterogeneous nitrogen inputs within the catchment, it was necessary to abandon the hypothesis of uniform recharge and to replace the calculations based on topographic index classes by an explicit cell to cell routing. Following the work from Crave and Gascuel-Odoux (1997) the hydraulic gradient was better estimated by the 'downslope gradient', i.e. the gradient between the elevation of the cell considered and the first stream cell reached when following the flow pathway. Conductivity was supposed to decrease exponentially with the depth like in the initial TOPMODEL version, but another profile could be adopted following catchment properties as suggested by Ambroise et al. (1996).

The watershed is modelled as a set of columns as shown on Fig. 1, each column corresponding to a cell of a grid digital elevation model (DEM). The flow direction is determined following the greatest elevation gradient between a cell and its eight neighbours. River cells are determined by a drainage area threshold: for the cells over this threshold the outflow is routed directly to the outlet. TNT is based on a water balance at each time step for each column of the watershed. The column is divided into two stores:

- the soil store, that can be seen as the retention porosity of the root zone, where water can be taken up by plants or evaporated;
- the drainage store, that can be seen as the drainage porosity of the soil and of the subsoil, with a fixed capacity $SZMAX$. The amount of water in this store (SZ) determines two zones: the saturated zone where the groundwater flows laterally, and the unsaturated zone (or vadose zone) where water percolates vertically. When the drainage store is full ($SZ = SZMAX$), the vadose zone disappears and overland flow is generated.

Retention porosity under the soil is not taken into account.

In this coupled version of the model, the soil store is controlled by STICS, which simulates crop uptake, evapotranspiration, vertical water fluxes, and nitrogen transfers and transformations after rain and fertilization. Drainage water and nitrogen leaching under the soil calculated by STICS at each time step are summed with the surface fluxes calculated from the upslope cells to enter in TNT's drainage store. If the water input is higher than the capacity of the unsaturated zone, excess water forms overland flow at the surface. The percolation of water from the vadose zone to the saturated zone is controlled by the amount of water in the vadose zone (SUZ) and a maximum percolation rate given by Darcy's law at the interface between the two zones with a hydraulic gradient equal to 1:

$$Qp(t) = \text{minimum}(K_0 \exp((SZ(t-1) - SZMAX)/M); SUZ(t)) \quad (1)$$

where K_0 is the vertical hydraulic conductivity at the soil surface at saturation (m day^{-1}); M the exponential decay rate of the hydraulic conductivity with depth (m); $SZ(t-1)$ the saturated water content at time $(t-1)$ (m^3 m^{-2}); $SZMAX$ the maximum water content in the saturated zone (m^3 m^{-2}); $SUZ(t)$ the water content in the unsaturated zone and $Qp(t)$ the percolation (m^3 m^{-2} day^{-1}).

Percolation and deep groundwater flow from the upslope cells $Qb_u(t)$ increase the saturated zone content $SZ(t-1)$. Lateral flow to the downslope cell is calculated using Darcy's law, and is separated into two different flows, $Qb(t)$ and $Qes(t)$, depending if the groundwater level is above a threshold (SZT) (Robson et al., 1992):

If $SZ(t) < SZT$:

$$Qb(t) = T_0 \tan\beta(\exp((SZ(t) - SZMAX)/M) - \exp(-SZMAX/M)) \quad (2)$$

$$Qes(t) = 0 \quad (3)$$

If $SZ(t) > SZT$:

$$Qb(t) = T_0 \tan\beta(\exp((SZT(t) - SZMAX)/M) - \exp(-SZMAX/M)) \quad (4)$$

$$Qes(t) = T_0 \tan\beta \exp((SZ(t) - SZMAX)/M) - Qb \quad (5)$$

where SZT is the threshold above which subsurface flow is generated (m^3 m^{-2}); $Qb(t)$ the deep groundwater flow (m^3 m^{-2} day^{-1}); $Qes(t)$ the subsurface flow (m^3 m^{-2} day^{-1}); $\tan\beta$ the

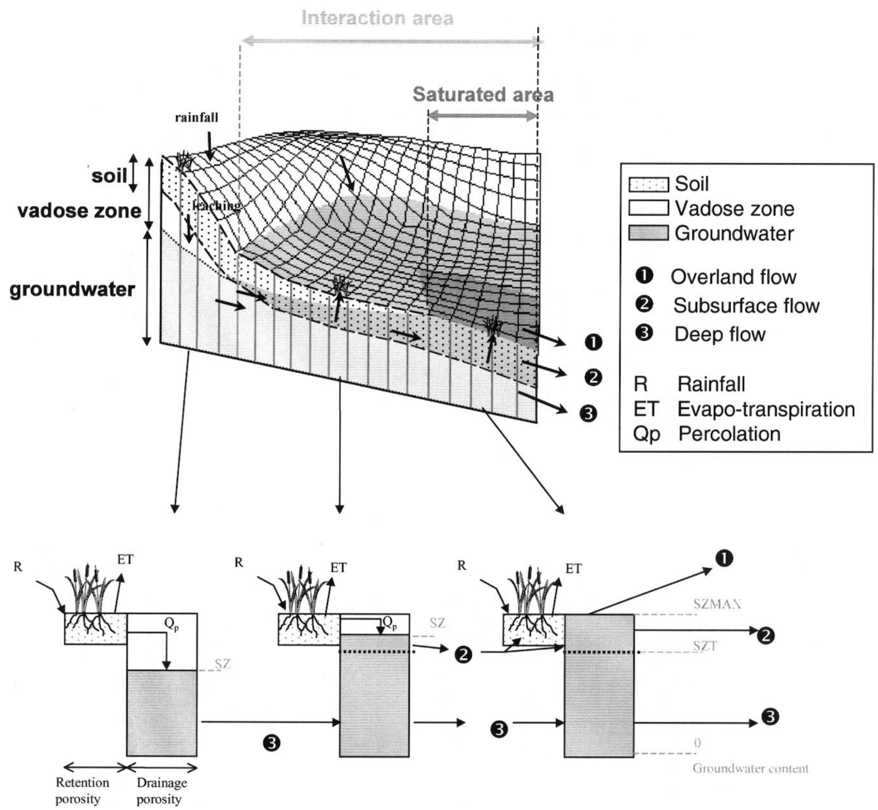

Fig. 1. Diagram of the catchment representation in the integrated model.

downslope gradient (–); and T_0 the lateral transmissivity at saturation (m^2 day^{-1}).

The deep groundwater flow is routed to the downslope cell saturated zone whereas the subsurface flow is routed to the surface. This water enters the soil zone controlled by STICS, and nitrates are exchanged between soil water and subsurface water. This process permits exchanges of nitrate and water between soil and groundwater, and the regions where this subsurface flow occurs are thus called the 'interaction area' in the following text.

Nitrate is considered as a perfect solute in the hydrological model, and the mixing in each reservoir is instantaneous and complete.

The model parameters are the following: the effective vertical hydraulic conductivity at the soil surface (K_0, in m day^{-1}), the total lateral transmissivity of the column (T_0, in m^2 day^{-1}), the exponential decay factor of the hydraulic conductivity with depth, supposed to be the same vertically and laterally (M in m), the maximum amount of water of the mobile groundwater ($SZMAX$ in m), and the threshold above which subsurface flow occurs (SZT in m). These parameters can be different for each cell.

2.3. The crop model

Many crop models simulating nitrogen vertical fluxes and transformations in soils have been developed so far (see, e.g. Ball and Trudgill, 1995). STICS (Brisson et al., 1998) has been chosen because: (i) it simulates explicitly the effect of water and nitrogen stresses on crop development and growth; (ii) it is generic, i.e. its structure allows to simulate different crops with the same set of equations; (iii) it is relatively simple and the water transfer component is compatible with TOPMODEL; and (iv) it has been well parameterized and tested for winter wheat and maize under temperate climate.

The main processes simulated are the growth, the development of the crop and the water and nitrogen balance of the soil–crop system, organized in seven modules: development, shoot growth, yield components, root growth, water balance, thermal environment and nitrogen balance. STICS water input is rainfall at the soil surface and the model simulates evapotranspiration, water and nitrogen uptake by the plants, nitrogen transformations in the soil, and thereafter percolation and nitrogen leaching through the soil considered as a succession of horizontal layers as in Burns' model (Burns, 1974).

This model has been slightly adapted to take interactions between cells into account in addition to the existing transfers. Water of the subsurface flow coming from upslope cells, calculated by TNT, is mixed to the existing soil water in each layer that is not saturated, beginning from the bottom soil layer. If the layer is at field capacity, only nitrates are exchanged by homogenizing the concentrations between the subsurface flow water and the soil water. If the water content of the layer is under field capacity, it is filled up to the field capacity, and the remaining water moves to the next layer upwards.

When the organic layer is saturated by the groundwater, the mineralization rate of the soil organic matter is halved (Van Der Linden et al., 1987), and denitrification is activated. The denitrification rate is calculated using the NEMIS model (Hénault, 1995) adapted to the saturated soils and the local context:

$$VED = VPD \cdot f_T \cdot f_N \tag{6}$$

where VED is the actual denitrification rate (kg N ha^{-1} day^{-1}); VPD the potential denitrification rate (kg N ha^{-1} day^{-1}), at 20°C under anoxic conditions and with excess of nitrate (here taken as 30 kg N ha^{-1} day^{-1} according to Durand et al., 1998); f_T, a temperature function following an Arrhenius law; and f_N, a function of nitrate concentration following a Michaelis–Menten law.

The code of the model has been modified to allow multiple soil column and multiple crop simulation, and the model is run for each cell at each time step.

2.4. Simulation protocols

Simulations are conducted on square virtual catchments of 400 square cells 40 m wide, i.e. a total area of 0.64 km^2 (Fig. 2). The elevation range is 26 m. Two slope profiles were chosen:

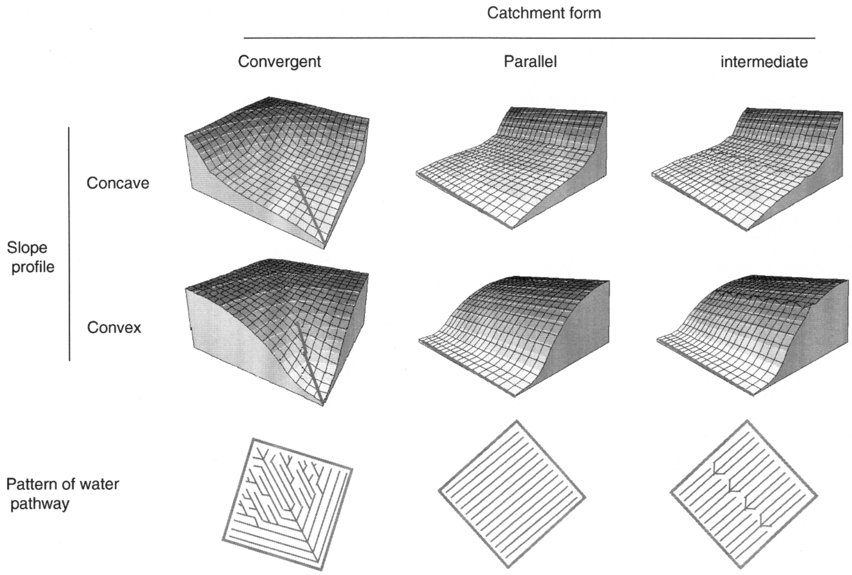

Fig. 2. Aspect of the six types of virtual catchments.

one features a wide valley bottom, called 'concave', the other features a narrow valley bottom and an extended plateau, called 'convex'. These slope profiles were used to generate a catchment, either by rotation around the lowest point to form a headwater catchment, called 'convergent', or by translation to obtain a regular hillslope, called 'parallel'. An 'intermediate' type was constructed by introducing higher spots in the middle of the parallel catchment. This constitutes six geomorphological types of catchments, called in the following text: Cc, Cv, Pc, Pv, Xc, Xv with C standing for convergent, P for parallel, X for intermediate, c for concave, v for convex. These catchments can be seen as stereotypes of the relief elements of a temperate area on crystalline bedrock.

The soil of the catchments was considered as being homogeneous and having the mean properties of the soil of the experimental catchment of Naizin (Britanny, France): depth of 80 cm, field capacity of 180 mm, a plough layer 20 cm thick, 17% clay and 2.4% organic matter (Walter and Curmi, 1998).

The catchments were divided into 16 square parcels of 25 cells (i.e. 0.04 km^2) each. In half the parcels, agricultural practices resulting in a strong excess of nitrogen ('source' parcels) have been simulated. In the other parcels, the simulated applied nitrogen was lower than the crop requirements ('sink' parcels). The simulation exercise consisted in comparing the nitrogen fluxes in the six constructed catchments with the source parcels either upslope or downslope. In the parallel case, a chequered' distribution of the source and sink parcel has also been tested.

The parameters used for the source and sink crops are those established by the authors of the STICS model for maize and wheat, respectively. Overfertilized maize is actually considered as an important source of nitrate because of a short cycle and a poor nitrate absorption capacity. On the other hand, under-fertilized winter wheat can be considered as a potential sink of nitrate because of a relatively high uptake capacity and a long cycle. The agricultural practices have been adapted to these crops (Table 1). Both grain and straw are harvested for the two crops (as silage for maize) and the roots only are left in the field.

Mean nitrogen fertilization on the whole catchment is of 250 kg N ha^{-1} $year^{-1}$, 80 kg as mineral N and 170 kg as cattle slurry. The figure of 170 kg N ha^{-1} $year^{-1}$ is the EU standard for maximum organic N load to crops. Mineral fertilizer is applied on the whole catchment while manure is applied on the source parcels only. It is supposed that 30% of the nitrogen of the slurry is volatilized during spreading; the remaining part (i.e. 158 kg N ha^{-1} $year^{-1}$) is considered as being spread on the source parcels at two dates, and treated by the model as mineral N.

Another series of simulations has been conducted to test the effect of nitrogen deficit of the sink parcels. Different amounts of mineral fertilizer (0, 40, 80, 120, 160, 200, 320 and 440 kg N ha^{-1} $year^{-1}$) are applied on the sink parcels, one quarter on 15 February and the other part on 31 March. Source parcels fertilization is kept at 250 kg N ha^{-1} $year^{-1}$. It is important to note that in these simulations, the total nitrogen input to the catchments varies between the simulations.

Climate data were obtained from measurements on the Kervidy catchment (Brittany, France) during 1994, 1995 and 1996. These 3 years show contrasted features, both in amount and in distribution of the rainfall, which represent quite well the climate variations of Brittany. Three successive cycles of these 3 years were simulated, the first two being used for initializing the system. A steady state is established between the second and the third cycle.

The results presented here are the means of the third cycle of 3 years. Parameters used for the hydrological model were obtained by a step by step calibration in the Kervidy catchment for these 3 years.

Table 1
Cultural practices

'Sink' crop (wheat)	
October 24	Sowing
February 15	20 kg N ha^{-1} (mineral fertilizer)
March 31	60 kg N ha^{-1} (mineral fertilizer)
July 24	Harvest
'Source' crop (maize)	
March 1	170 kg N ha^{-1} (slurry)
April 15	170 kg N ha^{-1} (slurry)
May 7	Sowing
May 7	80 kg N ha^{-1} (mineral fertilizer)
September 30	Harvest

3. Results and discussion

3.1. General observations

The first set of results presented was obtained with the six geomorphologic types, crossed with the two types of spatial distribution of the crops (source parcels upslope or downslope) and only one level of mineral fertilization, i.e. 12 simulations.

The mean annual specific discharge varied only between 416 and 429 mm for a mean annual rainfall of 850 mm for the 3 years studied. An example of specific discharge simulated on the parallel concave catchment is shown in Fig. 3. Comparison with the specific discharge of the Kervidy catchment showed that the model simulates the discharge dynamics of a catchment in Brittany fairly well. The mean actual evapotranspiration was 430 mm, 187 mm of which being evaporated and 243 mm transpired.

The mean nitrogen export by crops was of 148 ± 18 kg N ha^{-1} $year^{-1}$. The mean export by the 'source' crop was fairly steady (149 ± 5) while that of the 'sink' crop which was more variable (147 ± 35).

The spatial patterns obtained are presented in Fig. 4. The maps show discontinuities that are linked to artefacts in the DEM construction or analysis. In particular, mono-directional drainage network derivation causes non-realistic patterns of saturation in the convergent catchments (for a full discussion on mono-directionnal and multi-directionnal drainage network derivation methods, see Wolock and McCabe, 1995; Beaujouan et al., 2000). The treatment of the river cells and the computation of downslope gradient calculation also lead to minor irregularities in the parallel catchments. However, these artefacts do not affect significantly the results.

The maps of the mean duration of the interaction period (Fig. 4(i)) show that the size of the interaction area varied with catchment morphology. An interaction index was constructed for each catchment to represent the spatial and temporal extent of the interaction area: this index is equal to the mean daily proportion of the catchment area where subsurface flow occurs. Fig. 5

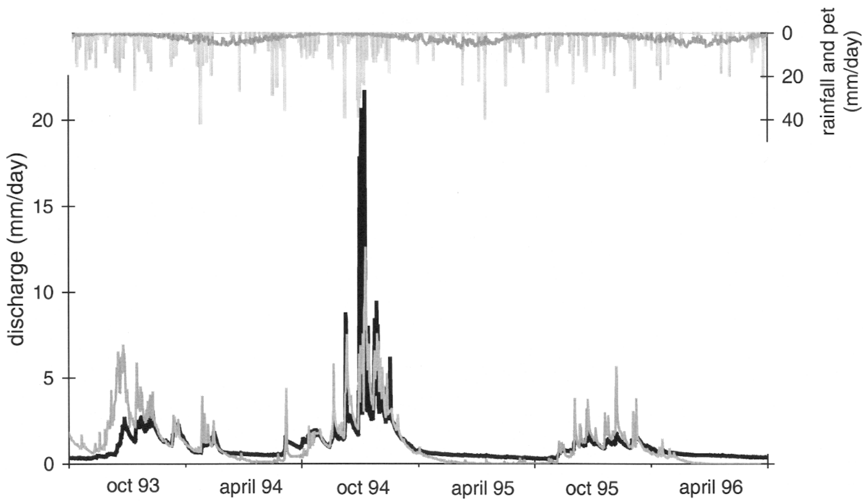

Fig. 3. Simulated specific discharge at the outlet of the 'parallel concave' catchment (black line) compared to the specific discharge observed at the outlet of the catchment of Kervidy (Brittany, France) (grey line). On the secondary Y-axis are plotted the daily rainfall (grey bars) and evapotranspiration (black line).

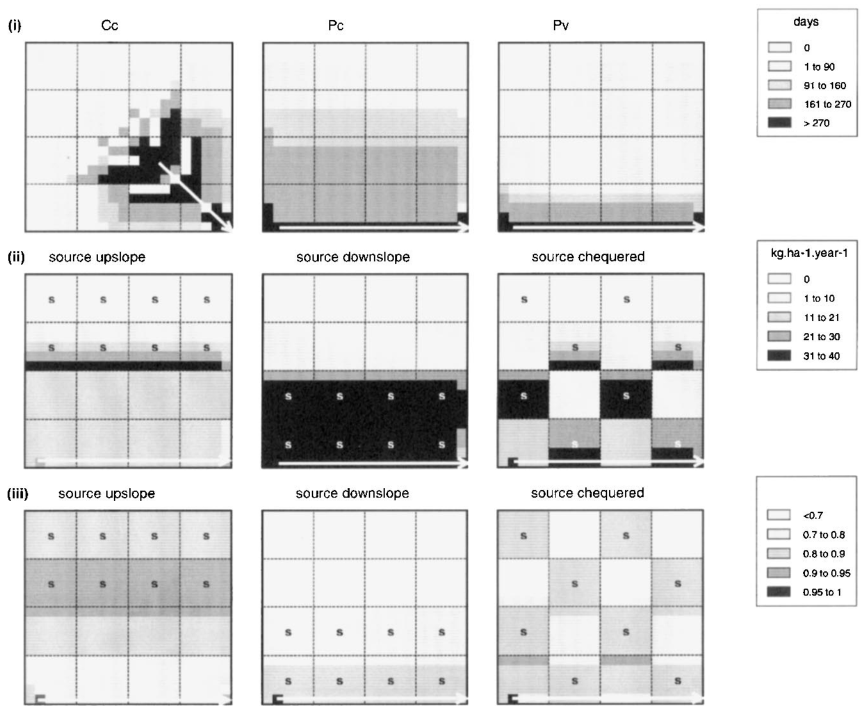

Fig. 4. Maps of the mean values of different variables for the last 3 simulation years: (i) mean duration of the interaction periods (expressed in days year^{-1}) on three catchment types: Cc: convergent concave; Pc: Parallel concave; Pv: Parallel convex. (ii) Mean denitrification (kg N ha^{-1} year^{-1}) on the parallel concave catchment depending on the location of the crops. (iii) Mean nitrogen stress index (INN) during the reproductive phase of the crop on the Parallel concave catchment depending on the location of the crops. 's' letter indicates the position of source crop parcels. Outlet of each catchment is on the bottom right.

shows two major trends: convex catchments have a smaller index than concave ones; convergent catchments have a smaller index than the catchments with a parallel structure, namely the parallel and intermediate ones.

3.2. Effect of spatial arrangement of crops on stream pollution

The mean nitrate concentration in the river over the 3 years of simulations for each catchment and for the different crop distributions is given in the Table 2. This concentration was almost the same for the six catchments when the source crops were located on a downslope. It was lower and more variable when the source parcels were located on an upslope. The difference in concentration due to the change in crop location represented 12–34% of the maximum concentration: spatial distribution of the crops may well significantly affect water quality by mean of exchanges between soil and groundwater.

This effect varied with catchment morphology. Fig. 6 shows that, in the cases studied, the effect of crop location is strongly linked to the interaction index. This interaction index accurately synthesizes the environmental characteristics favouring the effect of a change in the crop spatial distribution.

3.3. Origin of this effect

The general trend observed while changing the distribution of crops were the same for all the catchments. The following analysis focuses on the catchment for which the most important effect was obtained, i.e. the parallel concave catchment.

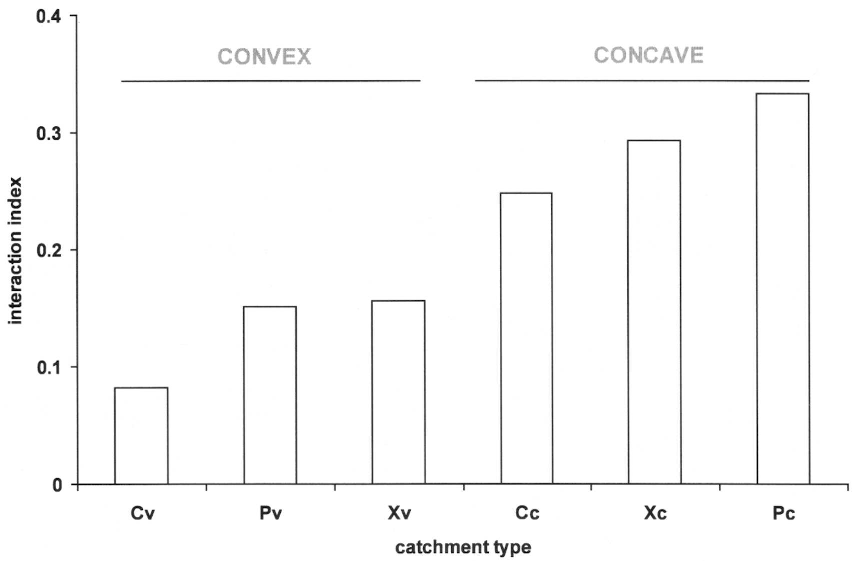

Fig. 5. Interaction indexes calculated for the different catchment types. The interaction index is defined as the mean daily proportion of the catchment area where subsurface flow occurred.

Table 2
Mean streamwater nitrate concentration (mg NO_3 l^{-1}) for each catchment type, depending on crop location

	Cc	Cv	Pc	Pv	Xc	Xv
Source crops downslope	161	171	157	167	163	166
Source crops upslope	127	151	103	139	113	136
Difference (% of max. concentration)	21	12	34	17	31	18

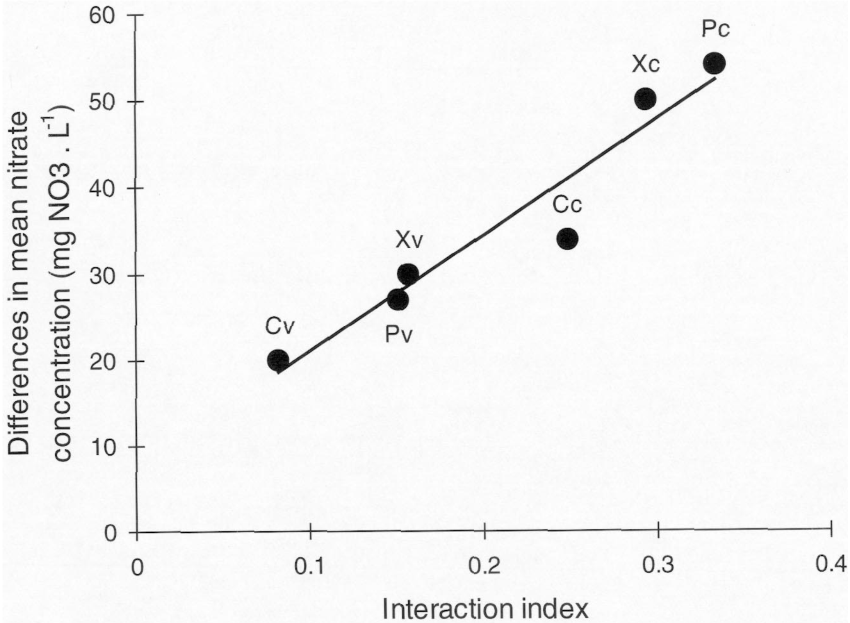

Fig. 6. Difference in mean nitrate concentration at the outlet of each catchment induced by the change in crop location (concentration when source parcels are located downslope minus concentration when parcels are located upslope), as a function of the interaction index.

Three different simulations were made by changing the location of the source parcels: upslope, downslope or chequered.

The gross input of nitrogen (i.e. by rainfall, mineralization and fertilization) was roughly the same for the three simulations, namely 294 kg N ha^{-1} year^{-1}. The amount of nitrogen stored in the soil and groundwater was also almost the same for all three simulations after the 3 years. Therefore, the variations in nitrogen discharge in the river were due to denitrification and exports by the crops only.

The mean simulated denitrification on the whole catchment was 9, 12.5, and 17 kg N ha^{-1} year^{-1} when sources were upslope, chequered or downslope, respectively. The maximum denitrification rate simulated for a cell was 51 kg N ha^{-1} year^{-1}. These values are low in comparison to the potential denitrification rate chosen (30 kg N ha^{-1} day^{-1}, i.e. 10 950 kg N ha^{-1} year^{-1}, Durand et al., 1998). The spatial distribution of denitrification is shown in Fig. 4(ii). Denitrification is obviously located in the potentially saturated areas, but it is sometimes low even for the cells with lasting saturation. This result suggests that denitrification was essentially limited by nitrate availability, which has also been observed in the field (Durand et al., 1998). Moreover, high denitrification rates are located in the source parcels. In these simulations, denitrification was more efficient if nitrogen was applied right into the most humid areas: nitrate exchanges between groundwater and soil water were of secondary importance for denitrification.

Mean nitrogen export by the crops was 127, 155, and 180 kg N ha^{-1} year^{-1} when source

Table 3
Amount of nitrogen exported by crops (kg N ha^{-1} year^{-1}) for the parallel concave (Pc) catchment as a function of crop location

	Location of source crops		
	Downslope	Chequered	Upslope
Sink crops	116	167	204
Source crops	138	144	155
Mean exports	127	155	180

parcels were upslope, chequered or downslope, respectively. This variation was essentially due to export by sink crops, as shown in Table 3. Export by sink crops depended to a great extent on their location with respect to source crops: the highest export took place in sink parcels downslope from the source parcels. The increase in export was larger when the sink parcels were located immediately downhill the source parcel, but it still existed even far away from the source parcels. The maps of nitrogen stress indexes during the reproductive stage of the crop (Fig. 4(iii)) show that the improvement in nitrogen nutrition of the sink crops is significant even for the cells remote from the source parcels. As opposed to the case of denitrification, nitrogen exchanges between groundwater and soils may play an important part in the nitrogen nutrition of crops.

Fig. 7 presents the relative amount of the different nitrogen sinks for each spatial distribution of crops. Denitrification accounted for only 5% of the total output. In this study, denitrification did not play a significant role in streamwater river pollution. Variations in nitrogen export by the sink crops explained most of variations in nitrate concentrations.

3.4. Effect of the sink crop fertilization

The effect of the sink crop fertilization rate was tested by additional simulation runs. The analysis was done on a third set of results obtained on the

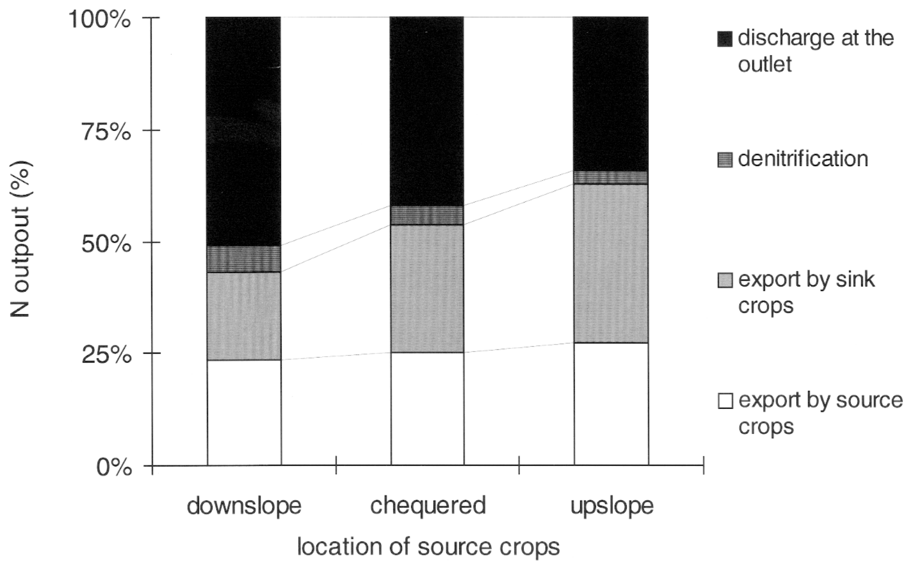

Fig. 7. Ratio of the different nitrogen outputs from the catchment as a function of the location of the source crops.

Table 4
Effect of the fertilization rate of the sink crops on the differences induced by the crop location in (i) nitrate concentration of the river (in % of the concentration with sink crops downslope) and (ii) amount of nitrogen exported by crops (amount with source crops downslope minus amount with source crops upslope, in kg N ha^{-1} year^{-1})

	Sink crop fertilization (kg N ha^{-1} year^{-1})							
	0	40	80	120	160	200	320	440
Difference in nitrate concentration of the river (%)	74	63	53	42	34	27	11	3
Difference in amount of N exported by crops (kg N ha^{-1} year^{-1})	66	59	53	47	41	35	20	9

parallel concave catchment, with two spatial distribution types (sink crops upslope or downslope), and eight nitrogen fertilization rates, i.e. 16 runs.

Results given in Table 4 indicate that the effect of spatial distribution of crops decreased when the fertilization rate of the sink crop increased. However, this effect still existed even when the fertilization rate was much higher than the rates actually used by farmers. This means that the model allows very high 'luxury consumption' by the wheat. However, the model does not account for the negative effects of excess nitrogen and waterlogging on crop development. For the highest fertilization rates, the model equations may not be applicable anymore. Still, these results suggest that downslope parcels, even when well fertilized, can still uptake a significant part of the nitrate transported by the groundwater.

4. Conclusion

The combined hydrology and crop nitrogen model presented here was a prototype aimed at assessing the interest of this modelling approach and giving a first order of magnitude of the crop location effect on nitrogen losses in rural catchments. By keeping the hydrological approach very simple, and capacity-based, it has been possible to build up a robust model, using few parameters, able to simulate the main hydrological processes observed in the real world catchments of northwestern France. The co-operation between the two programs was operational, although not optimal both from the computing and conceptual viewpoints: it was relatively slow and did not allow simulation of a fully lateral subsurface flow (the simulated flow was first vertical in STICS and then lateral in TNT). STICS is currently being simplified and rewritten to fit in the modular code architecture of TNT. The preliminary results give an incentive to develop both modelling and experimental investigations on the effects of the spatial distribution of crops on the nitrogen losses of rural catchments. The model still needs thorough testing and validation before it can be used to predict the response of real world catchments.

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