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WATER AND NITROGEN TRANSFER STUDY THROUGH SOILS OF A SMALL AGRICULTURAL WATER CATCHMENT

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ABSTRACT

Water and nitrogen movements in a small watershed (32ha) located in the Belgian Lorraine (south-eastern Belgium) were monitored intensively between 1988 and 1991 to investigate at a daily time step the possibility of predicting water discharge rates and nitrate concentrations in a spring if one knows the surface agricultural practices in the catchment area. The watershed was equipped with instruments to monitor the various meteorological, pedological, agronomic and geohydrological parameters assumed to explain most of the behaviour of water and nitrogen fluxes. They were recorded at various levels, i.e., the surface, vadose zone, saturated zone, and watershed outlet. Field observations were made to cross-check fluxes at each level. This information was then used in simulation models (SOIL and SOILN) to describe the movement of water and nitrogen solutes in the vadose zone and with original programming that describes their movements in the groundwater down to the outlet. These models present many parameters, the most sensitive of which were subjected to Monte Carlo Analysis which confirmed the robustness of the approach. The performance of the comprehensive model is quite satisfactory, with a 10% error in nitrogen fluxes over a three-year period. It shows the limits of such an approach despite the particularly intense degree of observation. © 1999 Published by Elsevier Science Ltd on behalf of the IAWQ. All rights reserved

KEYWORDS

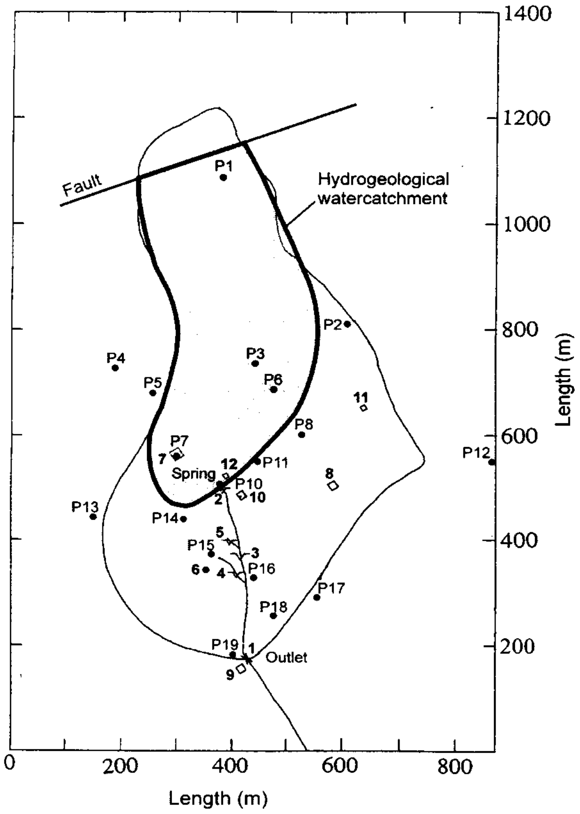
Agricultural watershed; nitrates; soil model; soil nitrogen dynamics; soil water dynamics.

INTRODUCTION

The production-oriented agriculture of the '60s through the '80s has given way little by little to sustainable agriculture which strives to maintain its productive potential without harming the environment. Farmers must be helped to deal with this transformation by enabling them to allow better for all aspects of a henceforward much more extensive system, since they must be interested in what goes on beyond the root system. There are many descriptive models of water and nitrogen transfer in soils, whether at the plot (Vereecken *et al.*, 1989; Wagenet and Hutson, 1989; Kragt *et al.*, 1989) or watershed scale (Larocque and Banton, 1995; Bouraoui *et al.*, 1997; Reiche, 1994; Styczen and Storm, 1993). Some studies have made it possible to compare them with each other or with a set of selected measurements (Reiniger *et al.*, 1991). The results of these comparisons are not always good and reveal the limits of modelling to describe water and nitrogen fluxes in soils. Considering the catchment area, the system becomes more complex as the problem of the models' intrinsic limitations is compounded by the greater difficulty of describing the 'catchment area' or 'watershed' correctly. Very few studies specify the methods used to get the parameter values from field observations. How does one acquire the data, most of which are field data, to optimise data collection and the models used? We shall focus in particular on the main difficulties which are not necessarily those envisioned at the start of an experiment. We shall also present the approach that we have used as it has yielded good results although it can still stand some improvement.

PRESENTATION OF THE SITE

The head of an entirely agricultural 32-hectare watershed was chosen for the experiment (Figure 1). This area is located in the Belgian Lorraine, in south-eastern Belgium. It is drained by a stream, *le ruisseau de la Fontaine*, which is a tributary of the Semois. Geologically, it consists of a several-meters-thick layer of Sinemurian sands and sandstone overlying Hettangian marls which form the base of the aquifer. Several meters of heterogeneous Quaternary loam are commonly found on top of the Sinemurian sand.



Legend :
1. Outlet Parshall venturi
2. Spring H-flume
3. Flow discharge 'mi-chemin' V-weir
4. Flow discharge 'ru super' V-weir
5. Flow discharge 'trop plein' V-weir
6. Small spring
7. Main station (sandy loam)
8. Cereals station (loamy sand)
9. Fallow station (loamy sand)
10. Meadow station (loamy sand)
11. Maize station (loamy sand)
12. Cereals station (sandy loam)

P-- : Piezometer

Figure 1. Presentation of the test area.

Table 1. Agricultural practices on the site (three-year means)

Crop	Area (ha)	Fertiliser (kg N/ha)	Crop N uptake (kg N/ha)	Nitrogen balance (kg N/ha)
Hayfield	2.42	50 + 25 T manure 1X/3years	100	-25
Forest	5.36	0	30	-20
Pasture	7.77	40	47	-3
Cereals	9.96	90	88	9
Roads	2.65	0	0	20
Alfalfa	0.50	50	213	57
Potato	0.21	110 + 50 T manure	59	144
Maize	2.70	135 + 50 T manure	174	227

The calculation of the nitrogen balance integrates the other terms of the balance, i.e., denitrification, symbiotic fixation (see alfalfa), and natural inputs.

The area studied is used for non-intensive traditional agriculture involving mixed cropping and herding. Pastures and hayfields cover the agricultural land, interspersed with some cereals (wheat, barley, oats and spelt) with maize and potatoes serving as lead crops in the crop rotation (Table 1.). The only possible source of pollution in this area is diffuse agricultural sources. In addition, the shallow groundwater (3-4 meters) means that surface applications of nitrogen can be detected in the spring fairly quickly (Debbaut *et al.*, 1991). The watershed underwent intensive field monitoring to understand its functioning better (see Figure 1 for the instrument locations). A few instruments set up on the site are mentioned in the following Methods section.

METHODS

Describing a system as complex as that of a watershed to allow a description of the water and nitrogen transfers that occur within it requires that a certain number of very useful rules and arrangements be respected to increase the monitoring chances of success.

Degree of accuracy

Care must be taken in all system analyses to ensure a comparable level of accuracy in all the successive steps leading to the output. If one of the steps is less accurate the entire data processing chain will be affected. Conversely, it is also unrealistic to strive for a very high degree of accuracy for one step if the other steps cannot reach such a level of accuracy. This principle of accuracy level is fundamental for it enables one to target better the various types of observations to make. In practice, however, when one starts an experiment it is unfortunately not always easy to tell quickly which steps in the procedure will have the greatest impact on the input transformation into an output. As a rule the investigator will proceed by trial and error and by intuition, calling upon his experience. As his knowledge of the site improves his overall approach will improve accordingly. Usually he will not be able to conduct a complete statistical analysis of sensitivity until afterwards, at the end of data collection, when he manages to incorporate all the main elements affecting the system.

Models-measurements combination

The 'watershed' system is complex. It is also poorly known. The various measurements (temperature, soil samples, nitrogen concentration, etc.) are taken on only a tiny part of the whole. It is thus important to select the monitoring and sampling points correctly, especially by means of strict sampling schedules that are adapted to the agropedological context (stratified sampling). The sampling must also be carried out in line with well-defined goals (Beven, 1989). In this study, it was not necessary to have very accurate soil leaching values for each field in the catchment area. On the other hand the various ways of monitoring and sampling the soil had to be designed to ascertain correctly the water and nitrogen fluxes at the watershed outlet.

Field observations are often very costly in terms of time and money. To make them as cost-effective as possible they have to be combined with models that can extract more information from them than the user can, mainly because of the computer's greater computational abilities, especially in handling large amounts of information. The computer will enable us to determine quickly, at each time step, the water and nitrogen fluxes that move from one soil layer to another and from one grid to the other.

One must also find the right balance between the number and type of data and the model requirements. Some models require large amounts of data that are hard to obtain (Beven, 1989). All too often the lack of field data will prevent the optimal use of models. A model must be chosen in line with the available data or those that can be obtained within the budget and deadlines and in line with the aims which have been set out to achieve. In our case we have to reject overly mechanistic models built to describe physical, chemical, and microbiological processes in detail, just as we have to reject overly simplistic models that would not use our field data to best advantage and would offer no possibility of extrapolation. Our model has to be designed to help people take decisions. The level of detail of the mechanistic description of phenomena and the way of achieving the final result is not important, provided that it is robust, extrapolable, and yields results that do not stray too far from reality. We thus settled on SOIL and SOILN (Jansson, 1991; Eckersten and Jansson, 1991).

Checking procedures

To the extent possible, each step in the process of estimating the volumes and quality of water at the watershed outlet was checked before going on to the next step. Various types of verification were used and preferably combined, as Nicolas (1998) advises. We opted to describe our system by combining two production functions with two transfer functions for water and nitrogen. The production functions enable us to determine the amounts of water and nitrogen that will percolate beyond the root zone and recharge the groundwater before flowing finally into the watershed spring. The transfer functions describe the movements of these two substances within the soil profile and in the groundwater. The nitrogen transfer and production functions must be estimated after those for water because they depend on them.

Water production function. The water production function, which yields the percolated volume of water, is deduced from the balance in the root zone. The runoff term could be neglected after an intensive double-ring measurement campaign. Precipitation was measured accurately on the site and checked against the records of the closest weather stations along with the meteorological parameters to calculate potential evapotranspiration (ETP). Actual evapotranspiration (ETA) was obtained from ETP by fitting the parameters of the SOIL model to the soil water stock measured along tensiometer profiles in the five main soil-crop situations on the site. An overall check was also performed subsequently for the entire watershed having its outlet at the spring. With an area of the groundwater basin of 14.5 ha estimated by three different methods (Tychon and Baveye, 1996), much smaller than that of the water catchment, and shown in Figure 1, we can find ETA from the precipitation and volume of water discharged at the watershed spring. The precise location of the groundwater basin was possible only after a long and detailed field study that provided a better understanding of the bottom catchment behaviour (Tychon, 1993). This overall measurement of the watershed actual evapotranspiration gives only a general check of the entire watershed but it is an independent check that prevents gross errors.

This multi-scale approach is an interesting verification method. The size of our watershed allowed both an overall check and a monitoring at a large enough number of points to describe the watershed main characteristics. This mesoscale has the advantage of giving some explanations as to the origin and nature of the watershed total flux, for each zone behaviour is known. Inversely it also allows one to check specific fluxes, for the total flux is the integration of all the specific fluxes on the site.

Water transfer function. A precise estimation of the water transfer function requires sufficient knowledge of the soil hydrodynamic properties (hydraulic conductivity, soil water retention curve). These were established using a mixed approach combining laboratory analysis with field measurements, surface and deep measurements, and measurements in the saturated and unsaturated zones. The different methods results matched well in the unsaturated part and yielded nearly equal fluxes at the bottom of the unsaturated zone. However this approach was facilitated by the shallowness of the groundwater, which does not give the transfer function an opportunity to act on the water displacement time. Again, an overall check wrapped up the check list by comparing observed and simulated spring water discharges.

Nitrogen production function. The nitrogen production function was calculated in the same systematic way as that of water and we tried to achieve an acceptable degree of accuracy for each of the terms of the balance at the surface. Consequently, we emphasised the important terms of the balance, *i.e.*, the fertiliser applications and exports through harvesting. For the less important terms, such as denitrification and symbiotic fixation, we used values derived from the literature. The natural inputs from dry and wet deposits were measured directly on site. The exports were estimated in various ways, depending on the means available (based on farm surveys, field measurements, and harvest samples). These values were compared with the means for the region. The mineral fertiliser inputs were estimated from surveys made at all the farms in the watershed. The volumes of organic fertiliser, i.e., manure, that were applied were estimated by surveys and their quality was determined by standard values per type of stable which we checked by a few random spot checks.

This surface balance was then compared with the changes in the soil water and soil concentrations in the various monitored plots. Given the laboriousness of monitoring the soils, we opted for mixed monitoring, which enabled us nonetheless to detect spatial and temporal variations in the various soil profiles. This twofold monitoring over time and space is vital (Addiscott, 1993). Five sites of a few square metres representing the main soil-crop situations in the drainage basin were equipped with soil water cup samplers. Weekly sampling enabled us to monitor the soil nitrogen concentration with time at a minimal number of points. In addition, soil samples were taken from a certain number of selected plots twice a year, just before and at the end of the leaching period, to express the spatial variability of the soil mineral nitrogen reserves at these two critical periods of the year.

Nitrogen transfer function. To determine the nitrogen transfer function, ^{15}N-labelled nitrogen trials were carried out on undisturbed soil columns. These trials showed what was commonly accepted, that is, that water and nitrate nitrogen move through the soil at virtually the same speeds (Marx, 1991). However, applying this hypothesis to reality in the field failed for one of the two main soils studied, the best structured one: the movement of nitrogen that was simulated by the model exceeded by a long way the movement that was actually detected. This difference between the laboratory and field approaches is due to the nitrogen concentrations in the macropores of these well structured soils, which can be very different from those in the other pores of the soil (Tychon, 1993).

Just as for water, the concentration in the catchment spring was used as a rough check on the values of the nitrogen fluxes of the plots in the catchment area. We must also point out that no prior adjustment was made to get the calculated concentrations and those measured in the spring to match; it was thus a true check on the model.

Finally, we must point out that this approach was interdisciplinary and required the intervention of crop scientists, soil scientists, and geohydrologists. The combination of abilities and techniques from these various disciplines definitely led to a better grasp of the problem as mentioned by Vauclin (1990).

To wrap up, the various models we used involved some 100 parameters in all. Whilst we were able to describe the water and nitrogen fluxes, we had no idea as to the model robustness. A sensitivity analysis can answer this question.

The models

SOIL and SOILN have been described by Jansson (1991), Eckersten and Jansson (1991). These two software packages enable one to calculate water and nitrogen balances at 24-hour intervals in the unsaturated zone according to the principle of mass conservation. Concerning the groundwater movement and nitrogen transport, a simple one-dimensional system was devised. It consists of thirteen grids of various sizes, each of which represents a plot in the catchment area. This one-dimensional structure is possible because all of the plots are perpendicular to the main axis of flow. Nitrogen displacement is equal to that of the water. The water movement is governed by a head gradient corresponding to the difference in elevation between the central points of two adjacent grids and the horizontal distance between them. The volume that leaves each grid is the product of the unit flow rate leaving the grid multiplied by the cross-section of passage. This cross-section is obtained by multiplying the mean values of the widths of neighbouring grids by the mean thicknesses of the two groundwater grids. Finally, each grid is fed by a vertical flux of water and nitrogen corresponding to the contribution of the unsaturated zone and by one or two lateral fluxes from its neighbouring grids. The flux of water leaving the last grid simulates the flow at the spring.

RESULTS AND COMMENTS

Just as an illustration, Figure 2 shows a comparison of the water tensions measured in the field and those calculated by the SOIL model. The first year served to calibrate the parameters, the second year to validate them. In the calibration phase the parameters were adjusted to allow for the behaviour of the tensiometers over the entire profile as well. Indeed there is no sense adjusting the model results to a single depth if this prevents correct adjustment of the following depths. Thereafter, the parameters generated by these adjustments were used to model the water fluxes in all the areas of the catchment having the same soil and crop characteristics.

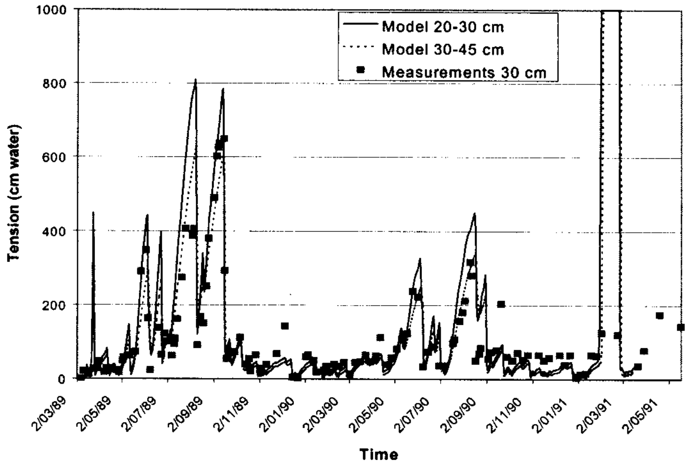


Figure 2. Water tensions in a sandy loam.

For the nitrogen fluxes, one check of the model outputs was carried out by comparing the field measurements (soil samples taken at 15 cm intervals to a depth of 150 cm at the start and end of the leaching period) with those generated by the model for the unsaturated zone. Figure 3 shows the results for 1989 (calibration) and 1990 (validation). The majority of the soil-crop situations in the area is shown in this graph. The results were satisfactory (correlation coefficients (R) of 0.93 and 0.89 for the calibration and validation, respectively). They enable us to assert that the description of the nitrogen fluxes in the unsaturated zone is correct for the catchment area as a whole.

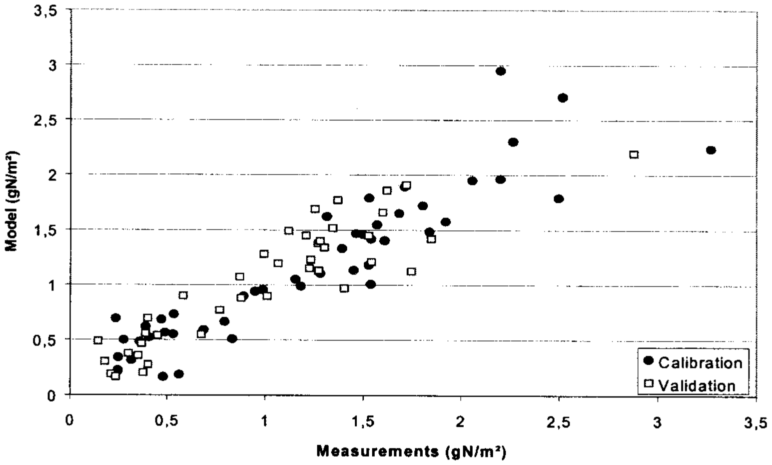


Figure 3. Nitrogen concentrations in several soil layers at different times in the 2-year study period.

When the nitrogen fluxes of each plot are summed and distributed over time by the transfer functions specific to each plot, it is possible to compare these fluxes with those measured at the groundwater basin output (Figure 4). Overall, the fluxes are correctly assessed. We nevertheless see that the model seems to react too sluggishly, whether at the start of the leaching period, when the nitrogen fluxes rise, or at the drying-up period, when the nitrogen fluxes decline too slowly. The model also appears to be totally unable to predict the very rapid surges in concentration seen notably at the start of the leaching periods.

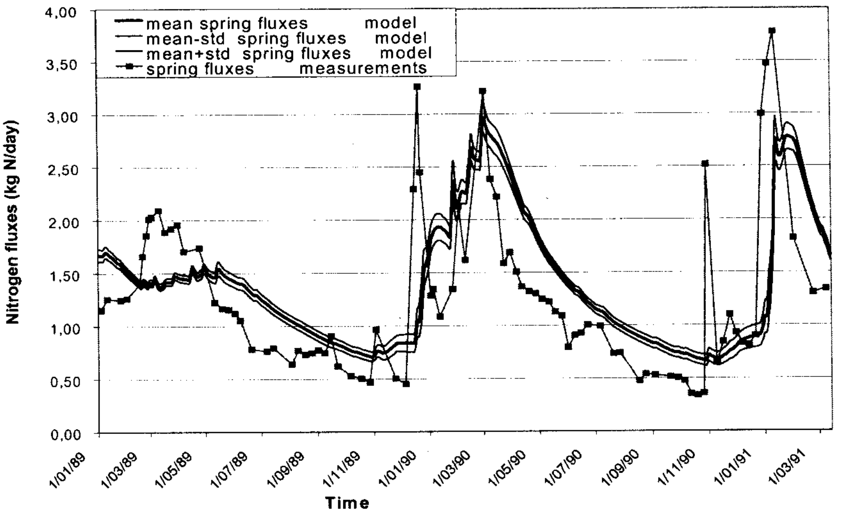


Figure 4. Measured and modelled nitrogen fluxes in the spring of the water catchment area (01/89-03/91).

We believe that this is due to the overly simplified approach used to describe water and nitrogen movements in the groundwater. The production function, on the other hand, seems to fit the observations better. The model overestimated the nitrogen flux over a three-year period by less than 10%, which is highly satisfactory. To determine the integrated model limits, we subjected it to a sensitivity analysis covering the parameters of the SOIL model, SOILN model, and groundwater model (71 parameters). No sensitivity analysis was performed on the entry variables (meteorological data, soil data). A first selection round reduced the analysis to the 23 most sensitive parameters which included albedo, aquifer porosity, the groundwater storage coefficient, the parameter that defines the critical tension at which the function of reduced water uptake kicks in, leaf resistance to transpiration, the roots carbon/nitrogen ratio, amount of fertiliser applied, efficiency of internal microbial biomass and metabolite synthesis in the litter, amount of nitrogen in the manure, microbiological activity response to a 10°C temperature rise, the function simulating nitrogen uptake by growing plants, and the reference temperature for monitoring microbiological activity. All of these parameters were subjected to sensitivity analysis in which their values were made to vary randomly over what was judged to be a reasonable range in 50 successive simulations (Monte Carlo Analysis). The distribution of the results shown in Figure 4 (means ± standard deviations) shows the integrated model that we used to be remarkably robust. Our fears of the impact of parameters that are difficult or impossible to obtain may thus be laid to rest. This analysis shows as well that it is highly unlikely that the differences between the measured and calculated values are due to uncertainty in estimating specific parameters. Consequently, the causes of such disparities must be sought elsewhere - in an insufficient spatial description of the groundwater, in our opinion. However, as a tool for farmers or watershed managers, it would be difficult to get more useful information than is provided by this study.

CONCLUSIONS

The principle of searching for the same degree of accuracy in all steps of the approach is to be praised although it is poorly adapted to the realities of the field. Indeed, it requires good initial knowledge of the system. This is never the case when working for the first time in natural environments as complex as watersheds. With hindsight we can say that the approach we used here was imperfect, notably because we underestimated the problem of describing the transfers in the groundwater. Too much time and effort was devoted to describing the unsaturated at the expense of the saturated zone which was not well enough understood. Setting up observation techniques to determine the most sensitive pertinent parameters in this type of comprehensive study must be a priority of future research if one wants the application of this type of approach to the catchment area scale to have any meaning. This study was the first 'life-sized' trial. It also showed that detailed field observations of a few parameters (macropore effect, groundwater basin limits) were required to go on to subsequent steps in this integrated approach. Strengthened by this experience, we are now using a similar approach that takes into account the difficulties encountered in the study reported here to investigate another site. This new experiment should reveal the approach exportability. Nonetheless our results can be considered satisfactory since we managed to model three-year cumulative nitrogen flows with a less than 10% error. Such results are sufficient for most watershed management purposes.

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