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Modelling the Effectiveness of Agricultural Measures to Reduce the Amount of Pesticides Entering Surface Waters

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Abstract In agricultural areas, pesticide concentrations in rivers can show a highly dynamic course frequently exceeding the standards. In order to diminish these high concentration peaks and to reduce their negative impacts on the receiving ecosystem, different measures can be taken. The objective of this study is to evaluate the impact of implementation of best management practices on pesticide fluxes entering surface waters using a modelling approach. We focus on the Nil catchment, a small basin situated in the centre of Belgium. From previous studies, the SWAT model (Soil and Water Assessment Tool) was calibrated and validated for hydrology and pesticide input for this basin. Different management scenarios were simulated and compared to the initial situation. The results revealed that strip cropping seems to be more efficient than the implementation of cover crops, than buffer strips, than a 25% reduction of point losses and plough management respectively. The study showed that a modelling approach can be used to estimate the impacts of water quality management programs in river basins. Such an approach allows to rank different mitigation measures for pesticide fluxes towards surface waters.

Keywords Management · Mitigation · Pesticides · River water quality modelling

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1 Introduction

It is known that pesticide pollution may pose a serious problem in upstream agricultural areas (Leu et al. 2004; Konstantinou et al. 2005; Claver et al. 2006). In order to reduce the negative impact on the receiving ecosystem (Van den Brink et al. 2000; Wendt-Rasch et al. 2004; Capkin et al. 2006), pesticide fluxes towards the river system can be diminished by means of different measures. For pesticide pollution, one can differentiate between point sources, e.g. the leakage of spraying equipment and diffuse sources such as runoff and drift. As point sources can contribute for 30–90% of the pesticide load in river systems (Leu et al. 2004; Beernaerts et al. 2005; Holvoet et al. 2007) it is important also to consider measures diminishing these losses.

In view of the Water Framework Directive (Barth and Fawell 2001), tools should be tested that integrate the management of all water resources at the river basin scale. By using catchment models, the impact of measures on hydrology, sediment transport, nutrients and pesticide loads can be assessed. Catchment models can quantify the effects of selected management actions (Behera and Panda 2006; Bracmort et al. 2006; Santhi et al. 2006; Bärlund et al. 2007). This can support decision makers.

The aim of this study is to gain insight in the effectiveness of different agricultural measures reducing the flux of pesticides towards a surface water.

2 Materials and Methods

2.1 Study Catchment

In this study, we focus on the small and hilly Nil catchment situated in the middle of Belgium. It drains an area of 32 km^2 and the river is 14 km long. The average elevation measures 151 m a.s.l., with the highest top reaching 167 m a.s.l. and the watershed outlet lying at 110 m a.s.l. The area consists predominantly of loamy soils, 7% of the area is inhabited and the main crops grown are winter wheat (22% of the catchment area), corn (15%) and sugar beet (10%). Eighteen percent of the catchment consists of pasture. The Nil basin forms an appropriate study area, as it was studied in detail for pesticide application (Beernaerts et al. 2005). Intensive monitoring campaigns were set up from 1998 till 2004 (Beernaerts et al. 2005; Holvoet et al. 2007). In this study, we focus on the use of the herbicide atrazine for the cultivation of corn (*Zea mays*) (Fig. 1).

2.2 The Adapted SWAT Model

SWAT—The Soil and Water Assessment Tool—(Arnold et al. 1998) is chosen for modelling catchment-scale pesticide fluxes to the river. It is a well-documented model with open source code, able to simulate hydrology, sediments, nutrients and pesticides (Neitsch et al. 2002c). Once optimised and calibrated, it can be used for optimising agricultural management (Behera and Panda 2006; Bracmort et al. 2006; Santhi et al. 2006; Bärlund et al. 2007).

SWAT was developed by the USDA (Arnold et al. 1998) to predict the impact of land management practices on water, sediment and amount of chemicals originating from agriculture, in large complex river basins with varying soils, land use and management conditions over a long period of time. It is a process-based and semi-distributed, continuous model with a daily calculation time step. It includes physically based equations and empirical relationships.

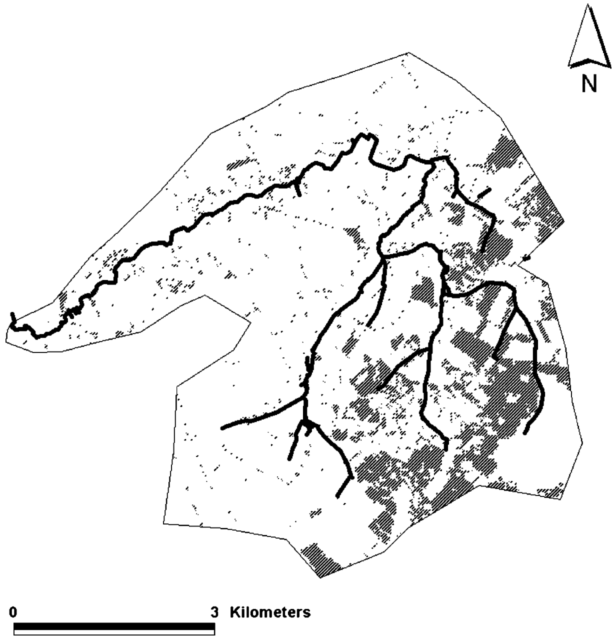

Fig. 1 The cultivation of corn (*grey area*) in the Nil catchment. The *black line* represents the river Nil

The water quantity processes simulated by SWAT include precipitation, evapotranspiration, surface run-off, lateral subsurface flow, ground water flow and river flow. The equations used to model the movement of pesticide in the land phase of the hydrologic cycle were adopted from GLEAMS (Leonard et al. 1987). SWAT simulates pesticide losses in surface runoff, sediments and percolation below the root zone. The movement of the pesticide is controlled by its solubility, degradation half-life both on plant foliage and in the soil, and soil organic carbon adsorption coefficient (Neitsch et al. 2002a).

In a previous study by Holvoet et al. (2005), a hydrologic model was calibrated for the Nil basin. The Nash–Sutcliffe coefficient improved from an initial value of −22.4 for the cold simulation, to +0.53 after calibration specific for spring. Then pesticide data were added to the model and the source code of SWAT2000 was adapted in order to take into account point losses (Holvoet et al. 2008). The model was calibrated for pesticides (see Fig. 2). For the year 1998, the Nash–Sutcliffe improved from a value of −2.63 to 0.66 for atrazine concentrations. Next, simulations could be run in order to compare the effectiveness of different measures on pesticide fluxes towards the river.

2.3 Measures to Reduce Point Pollution

As different studies have shown that point sources contribute significantly to the pesticide fluxes into surface waters (Neumann et al. 2002; Leu et al. 2004; Holvoet et al. 2005, 2007), an important measure to investigate is the reduction of point losses. Point losses are caused by the cleaning of spray equipment on paved surfaces, the leakage of tools, spills, etc. As shown by Beernaerts et al. (2005), sensitization of farmers regarding this issue by showing results of monitoring campaigns and proposing possible solutions, can result in an important reduction of point losses. Unfortunately, when the sensitization campaign was stopped, the contribution of point sources rose immediately.

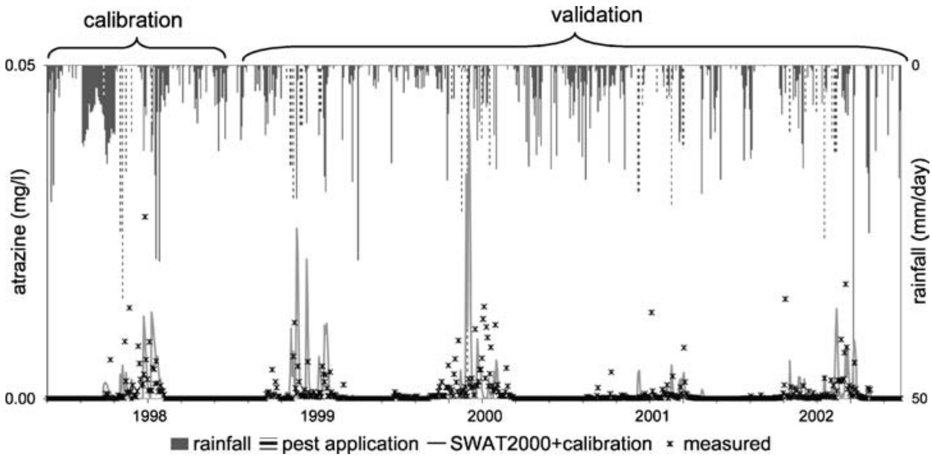

Fig. 2 Measured and predicted atrazine concentrations at the mouth of the river Nil after calibration (spring periods of 1998–2002)

In the adapted SWAT model described by Holvoet et al. (2008), the parameter 'AP_EF' (application efficiency coefficient) is the fraction of the applied pesticide which is deposited on the treated field. The remainder is diverted directly to the river system, i.e. as a direct loss (point loss + drift loss). By increasing the value of 'AP_EF', one can simulate the effect of reduced losses due to an increased awareness of farmers or to the presence of a biobed, biofilter or phytobac system on the farm.

During the simulations, it was assumed that the application efficiency has a constant value over the simulation period. However, in reality there will exist variability in time in the fraction of applied pesticides lost as a point loss due to day-to-day variations and in farmers customs.

2.4 Measures to Reduce Diffuse Pollution

Several best management practices (BMPs) can result in a reduction of pesticide fluxes towards the river. For Belgium, the following BMPs were worthwhile considering: residue management, sowing cover crops, contour farming, strip cropping and buffer strips.

- *Residue management*: In cropland, leaving sufficient residue on the ground after harvest and prior to tillage for planting will reduce sheet and rill erosion. However, farmers often plough the land after harvest and turn-around the soil, which brings less organic soil to the top which is more sensitive to erosion. Soils not covered by residue are more prone to erosion than the covered ones. By means of residue management, at least 30% of the crop residues or of the green manuring stays in the top layer of the soil. One can achieve this by different ploughing practices which are compared here. The corresponding values for mixing depth and mixing efficiencies of the different ploughing practices are given in Neitsch et al. (2002b).

The farmers in the Nil catchment plough their corn fields twice: once at the beginning of the winter period with a disk plough and once before seeding with a roller harrow. The different scenarios studied as ploughing alternatives are represented in Table 1. By means of a mouldboard plough only 5 up to 10% of the crop residues remain in the upper soil layer. On the other hand, with a chisel plough this value becomes 70%.

Table 1 Model parameters/management inputs used to represent the different BMPs

BMP		Changed parameters/management inputs
Residue management	Mouldboard plough	Instead of disk plough[a]
	Chisel plough	Instead of disk plough[a]
	Only seedbed preparation	No ploughing before winter
	Direct seeding	Bed preparation during seeding
Sowing cover crops	Mouldboard plough	Instead of disk plough[a] + rye; CN2: − 4
	Chisel plough	Instead of disk plough[a] + rye; CN2: − 4
	Only seedbed preparation	No ploughing before winter + rye; CN2: − 4
	Direct seeding	Bed preparation during seeding + rye; CN2: − 4
Contour farming		USLE_P: 0.6; CN2: − 3
Strip cropping		USLE_P: 0.3; CN2: − 6
Buffer strips		See detailed description

[a] See Neitsch et al. 2002b

- *Sowing cover crops*: To reduce erosion, it is recommended to cover the soil during the winter period with a crop. As corn is only harvested late, the possibilities for cover crops are limited to rye and grass. However, grass is not resistant against the herbicide atrazine. Therefore, we focus on rye as a cover crop. In the studied scenarios, rye is sown after corn harvest at the end of October. It is a hardy annual. To protect the soil from drying out before corn seeding, the rye is harvested or killed three weeks before, somewhere mid April. The SWAT manual suggests to change the value for the curve number CN2 (see Table 1).
- *Contour farming*: Crops grown in the sloping lands cause sheet and rill erosion and transport of sediments, nutrients and pesticides. With contour farming farmers plough and sow perpendicular to the contour lines, which strongly reduces the losses. The SWAT manual (Neitsch et al. 2002a) advises to change the value of the parameter USLE_P. This parameter is defined as the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down slope culture. Support practices include contour tillage, strip cropping on the contour and terrace systems. Besides the parameter USLE_P, the SWAT manual also suggests to change the value for the curve number CN2 (see Table 1).
- *Strip cropping*: Strip cropping has the same properties as contour farming, but in this case crops with different plant spacing are alternated. A dense crop is alternated with a less dense crop. As written before, the parameters USLE_P and CN2 should be adapted (Table 1).
- *Buffer strips*: Buffer strips have different filtering capacities through sedimentation and infiltration processes. In the original SWAT code (Neitsch et al. 2002a), the filter strip trapping efficiency for sediments, nutrients and pesticides is calculated as follows:

$$trap_{ef} = 0.367\left(width_{filtstrip}\right)^{0.2967} \tag{1}$$

where $trap_{ef}$ is the fraction of the constituent loading trapped by the filter strip and $width_{filtstrip}$ is the width of the filter strip (m). This formula has the following limitations:

– The maximum width of the filter strip that can be chosen is 30 m. Wider strips result in a trapping efficiency that equals 1: everything is retained by the buffer strip. In reality, this will not be valid under all circumstances and under all rainfall intensities.

- For each compound, a same fraction is retained in the buffer strip. In reality, there will be a difference between coarse and small particles and between dissolved and sorbed fractions. The coarser particles will sediment faster and pesticides for example are mainly bound to the small clay particles.
- The model does not take into account hydrologic variations in runoff scenarios. In reality, the trap efficiency will be different for storm events and normal rainfall events, i.e. the rain intensity will play a role.
- The model considers a buffer strip for a whole hydrologic response unit (HRU) (which is a lumped area with a unique combination of land use and soil in a subbasin) and not only for the fields that are situated truly along the river.

Therefore, the source code was adapted by extending the processes in the infiltration part and by adding a part describing sedimentation in the buffer strip. In this study, the exercise was made for two adjacent fields: one corn field and a buffer strip. The results were then extrapolated for all corn fields in the catchment situated along the river.

The extension of the infiltration part in the buffer strip, consisted of the addition of runoff from the corn field to the rainfall in the adjacent buffer strip. The considered amount of water can then infiltrate together with the dissolved nutrients and pesticides.

The sedimentation process was implemented in the source code as described below. Deletic (2001) found a correlation between the trapping efficiency for the sediment fraction s (particles of diameter d_s), $T_{r,s}$ (−), and the particle fall number $N_{f,s}$:

$$T_{r,s} = \frac{N_{f,s}^{0.69}}{N_{f,s}^{0.69} + 4.95} \tag{2}$$

$$N_{f,s} = \frac{b \times v_s}{h \times v_m} \tag{3}$$

where b is the width of the buffer strip (m); v_s the Stokes settling velocity of the particle d_s (m s^{-1}); h the depth of the flow (m); and v_m the average mean flow velocity between grass blades (m s^{-1}).The average mean overland flow velocity v_m is calculated in SWAT as follows:

$$v_m = \frac{q^{0.4} \times s^{0.3}}{n^{0.6}} \tag{4}$$

where q is the average overland flow rate considering a strip 1 meter wide down the sloping surface (m^3 s^{-1}); s is the slope of the buffer strip (estimated to be 0.1%) (m m^{-1}) and n is Manning's roughness coefficient (Neitsch et al. 2002a). The parameter q was calculated by means of the peak flow Q_{peak} divided by the width of the buffer strip. The peak flow Q_{peak} was used instead of the 24-h runoff average, as the latter would overestimate the real trapping efficiency. In SWAT Q_{peak} is calculated as follows:

$$Q_{peak} = \frac{\alpha_{tc} \times Q_{surf} \times A}{3.6 \times t_{conc}} \tag{5}$$

where α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm H_2O), A is the area of the subbasin (km^2), t_{conc} is the time of concentration for the subbasin (h) and 3.6 is a unit conversion factor. The time of concentration is the time for a drop of water to flow from the remotest point in the subbasin to the subbasin outlet. In order to determine the depth of flow h used in Eq. 3, the formula of Tollner et al. (1977) is implemented:

$$h = \frac{1.5 \times q \times n}{R^{2/3} \times S^{1/2}} \tag{6}$$

The two unknowns in Eq. 6 are the hydraulic radius R (m) and the distance S between the grass blades (m). The hydraulic radius equals $R = \frac{s \times h}{2 \times h + S}$ (Tollner et al. 1977). S is estimated to amount 4.5 mm (Gharabaghi et al. 2000).

The above mentioned equations are based on the assumption that no resuspension occurs. The inflowing sediment load in the buffer strip is divided into its three main fractions sand, silt and clay by analogy with the soil profile. Their respective average particle diameters (d_s) are 975, 24 and 1 μm.

3 Results and Discussion

3.1 Measures to Reduce Point Pollution

Different scenarios were compared, where each time the value of the application efficiency parameter AP_EF was slightly increased, corresponding to reduced point losses. The initial value for AP_EF reached after calibration was 0.998 (Holvoet et al. 2008). The results of the simulations for the year 1998 are presented in Table 2.

Table 2 illustrates that diminishing the point losses with 50% results in a decrease of the total atrazine load in the river with almost 20%. A reduction in point losses with 25% is estimated to result in almost 10% of load reduction in the river Nil during the year 1998.

3.2 Measures to Reduce Diffuse Pollution

The simulation results for the studied best management practices (BMPs) for corn cultivation in the Nil basin are presented in Table 3 for the year 1998. They allow ranking of BMPs for atrazine mitigation.

Before making any conclusions, it should be stressed that the change of the parameter values CN2 and USLE_P is based on literature. Model predictions are rather sensitive to the curve number CN2 (Holvoet et al. 2005). As a consequence, the performed study should be considered to provide a ranking in effectiveness of different measures rather than a quantitative assessment. To achieve the latter, field data would be necessary in order to be able to better parameterise the model for BMPs.

Table 2 Simulated load of atrazine in the river Nil during the year 1998 for different values of the application efficiency parameter, together with the percentage of increase or decrease compared to the initial atrazine load

Application efficiency	0.998	0.9985	0.999
Load of atrazine in solution (kg)	2.58	2.38	2.12
Increase (+)/ decrease (−) in load (%)	0	−8.8	−19.4

Table 3 Results of BMPs for the reduction of atrazine loads (g) in the river Nil for the year 1998

BMP		Increase(+)/decrease(−) atrazine load (%)	Percent of change dissolved atrazine	Percent of change sorbed atrazine
Residue management	Mouldboard plough	+0.9	−0.15	+19.90
	Chisel plough	−1.0	+0.33	−23.26
	Only seedbed preparation	−1.2	+0.57	−32.78
	Direct seeding	−1.4	+1.02	−43.84
Sowing cover crops	Mouldboard plough	−31.4	−32.12	−33.97
	Chisel plough	−32.1	−32.12	−47.16
	Only seedbed preparation	−32.3	−32.08	−51.51
	Direct seeding	−32.7	−32.04	−58.43
Contour farming		−26.9	−25.93	−56.50
Strip cropping		−38.7	−37.27	−80.79
Buffer strips	5-m width	−11.4	−11.64	−12.07

From Table 3 it is clear that strip cropping is the most successful practice for atrazine reduction in the Nil basin, both for the dissolved and sorbed atrazine fractions. It is followed by sowing cover crops and contour farming. The latter has its largest impact on the sorbed atrazine fraction. The construction of buffer strips results in a relatively limited decline in atrazine load. Hereby, it should be noticed that this measure was not applied on all corn fields as was done with the other measures, but only on corn fields situated along the river as is acceptable to farmers. Moreover, the model does not take into account runoff water coming from the fields situated above. Also, the buffering capacity is only calculated if a real grassed buffer strip is present. Modifications of ploughing practices seems the least efficient measure in this study.

4 Conclusions and Recommendations

A SWAT model is available for the Nil catchment that is validated for hydrology and pesticide input. This allows a ranking in effectiveness of measures for atrazine load reduction based on literature values for different parameters, rather than producing precise simulations. This ranking is directly linked to the sensitivity of SWAT to parameter changes and not necessarily to the efficiency of measures in the field. To state the latter, a validation of the scenarios by field data would be required. From this study strip cropping seems to be more efficient than the sowing of cover crops, the construction of buffer strips, a 25% reduction of point losses and finally plough management.

As indicated by Santhi et al. (2006), extensive monitoring data and intensive observation of best management practices are essential for assessing the effects of best management practices in a watershed. As for the moment there is no adequate literature available showing the quantitative benefits of best management practices for pesticide reduction, a modelling approach is very useful (Bracmort et al. 2006).

The resulting model needs further testing for other pesticides and other catchments. In future, the model can be used for comparison of different measures which can help decision makers.

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