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Characterizing hydrological connectivity to identify critical source areas for pesticides losses

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Abstract: In order to propose relevant pesticide mitigation strategies within agro-systems, i.e. grass strips or storm basins, it is necessary to identify the areas that mostly contribute to pesticide losses in surface water. At the agricultural catchment scale, this identification requires assessing the hydrological connectivity between plots and the river network. Indeed, a plot can be disconnected from the hydrological network if landscape components such as hedges block or limit the runoff generated. Conversely, some elements as ditches or road network can facilitate the runoff from upstream to downstream areas and increase the pesticide losses.

This study is aimed at analysing the hydrological connectivity on a vineyard catchment located in the Alsatian piedmont (Rouffach, France). The Hohrain catchment, 40 ha, comprises more than 120 farming plots and a dense, mostly impervious road network. The transport of pesticides in surface water represents regionally a main threat because the runoff produced on the vineyard area rapidly flows towards downstream water bodies, which are closely linked to the large Rhenan aquifer. The physically-based model LISEM (Limburg Soil Erosion Model) is retained to perform this analysis. This fully distributed model allows taking into account the spatial and temporal variability of hydrological processes within the catchment. The simulated contributive fields approximately encompass only 12% of the total catchment. The results are consistent with direct rainfall-runoff events based observations in terms of contributive fields and contributive part of the road network. This study showed that a detailed integration of the connectivity at the catchment scale is crucial to closely assess the spatial variability of pesticides losses.

Keywords: *Hydrological connectivity, pesticide transfer, vineyard catchment, LISEM model*

1. INTRODUCTION

Reliable monitoring and prediction of nonpoint source pesticides pollution data are required by water quality managers and environmental risk regulators to maintain and achieve a good water quality status. In order to propose relevant mitigation strategies within agro-systems, i.e. grass strips or storm basins (Gregroire et al., 2008), it is necessary to identify the most contributive areas of pesticide losses to surface water (Frey et al., 2009). At the agricultural catchment scale, this identification requires an assessment of the hydrological connectivity between fields and the river network.

The hydrological connectivity analysis requires the identification of the water flow paths between each plots and the outlet (Bracken and Croke, 2007). These water flow paths vary according to the hierarchical organization of the main hydrological processes, i.e runoff, sub-surface flows or drainage (Frey et al., 2009). To be connected to the outlet, a field needs to be active in term of water transfer but also contributive, i.e. without disconnection until the outlet (Ambroise, 2004). Indeed, a field can be disconnected from the hydrological network if landscape elements such as hedges, are located downstream and hinders the runoff. Conversely, some elements such as ditches or road network can enhance the runoff movement from upstream to downstream areas while increasing pesticide loss.

Two complementary methods can be applied to characterize the hydrological connectivity at the scale of the agricultural catchment. First, a direct observation of runoff can be performed during rainfall event to identify both the contributive area in term of runoff and the main water flow paths. However, this method is restricted to the characterization of surface transfer, i.e. runoff, and associated to peculiar rainfall-runoff event. Hence, connected areas vary with space and time according to the initial moisture, the soils surface characteristics and the rainfall characteristics (Bissonnais et al., 2005). The modeling approach represents a second method to study hydrological connectivity. This last method presents the advantage of taking into account the temporal and spatial variability during rainfall event or between the different events. These two methods are closely related because improvement of the model calibration procedure relies on direct observations of runoff events.

Key criteria for selecting a model to analyse the hydrological connectivity are: 1) a physically-based approach of dominant processes observed on the studied catchment in order to compare the observed with the simulated processes, 2) the ability to take into account the spatial variability of parameters that control both the intensity of the hydrological processes (Jetten et al., 2003), and the landscape elements which can either hinder or enhance the surface runoff (Moussa et al., 2003), and 3) the availability and the quality of data on the studied catchment.

This study is aimed at analyzing the interest of a detailed integration of the connectivity at the catchment scale to identify the most contributive areas of pesticide losses to surface water. This analysis is performed with the physically based LISEM model (De Roo et al., 1996) chosen according the key criteria discussed previously. The analysis of the contributive areas of pesticide losses was applied on the vineyard Hohrain catchment (Rouffach, Haut-Rhin, France).

2. MATERIALS AND METHODS

2.1. Study Site

The monitored experimental Hohrain transitory runoff catchment area is located in the Alsatian vineyard (Rouffach, Haut-Rhin, France, latitude 47°57’9 N; longitude 007°17’3 E; altitude 284 m) (Figure 1). The area of the catchment is 42 ha. Exceptional annual precipitations can reach 867 mm (1999) and the smallest was monitored in 1953 (361 mm). The mean annual rainfall calculated since 1946 is 600 mm. Geologically, Würm loamy loess and Oligocene clayey conglomerates and marls, as well as compact calcareous substrate largely dominate in the upper and lower parts of the catchment, respectively. Calcosol represent the main soil type, which is mostly calcareous clay loam. The mean slope of the catchment is 15%. More than 68 % of the catchment is covered by vineyard crop (Figure 1). The soil occupation shows a gradient from mostly forested areas and partly orchard at the upstream of the basin to agricultural and vineyard areas nearer to the inlet. With more than 120 farming plots, it should be noted that the road network is dense, mostly impervious and represents about 6 % of the area of the catchment. The catchment area is characterized by nonpermanent runoff events whose discharges can only be recorded at the catchment’s outlet during intense storm rainfall. Within the catchment area, an experimental plot of 1500 m² allows to follow-up pesticide export in runoff at the field scale.

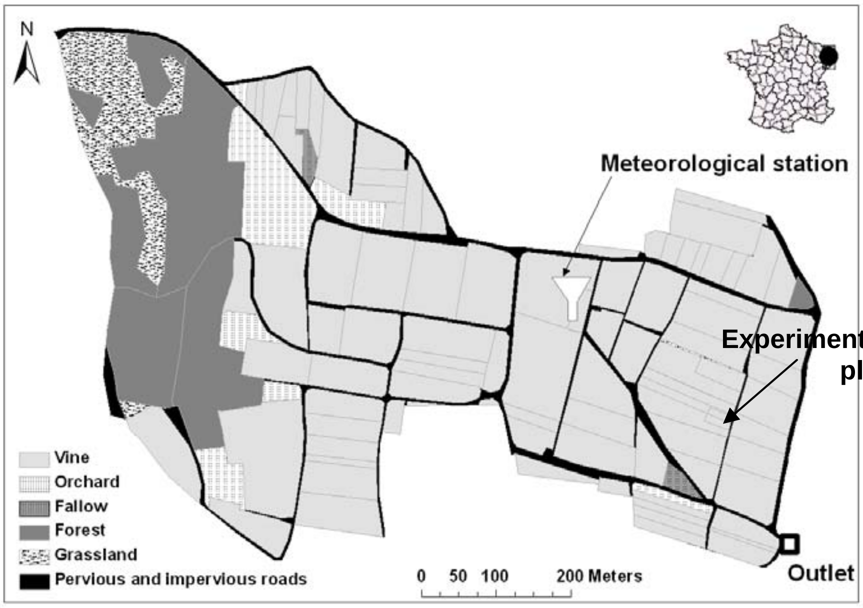

Figure 1. Delineation of the Rouffach catchment (Haut-Rhin, Alsace, France) and land use.

2.2. Geographic Database

A geographical database allows to extract and characterize elements of the topography that hinder or enhance surface runoff. This database includes:

- a digital elevation model performed with Lidar technology with a density of topographic information ranged between three points/m² for the downstream part and seven points/m² for the upstream part with a vertical accuracy of +/- 2.5 cm;
- a land use characterization with identification of soil and water conservation methods such as grass strips within or bordering the cropped area (Domange, 2004; Madier, 2007);
- a field-scale monitoring data including saturated hydraulic conductivity, porosity, relation between previous rainfall and initial soil moisture content, soil porosity, as well as e average suction at the wetting front and the soil depth (Tournebize, 2001; Madier, 2007).

Erosion components of the LISEM model were not used and the corresponding data are not described in this study.

2.3. Runoff Monitoring

Because of a major risk of transfer during the period between April to September, runoff events during this period were specifically monitored. Indeed, during the growing season, pesticides are applied and storm events are numerous, generating runoff with pesticide residues in the soluble phase.

Daily rainfall was collected at a meteorological station which is part the French national network and located within the study catchment. To examine the transport of pesticides, the sampling site was established along with the runoff that further discharges into a storm water protection basin at the outlet of the catchment area. The measurement of the water level was carried out with a Venturi channel (Endress and Hauser, Huningue, France) and was performed using a surface water level sensor. The station of flow measurement (DPN 7/2, Hydrologic, Sainte-Foy, Quebec, Canada) is coupled with a cooled fixed sampler (Hydrologic, Sainte-Foy, Québec, Canada). The sampling of water for subsequent analysis was controlled by water volume: one sample is taken each 8 m^3 streamed in the Venturi Canal. The concentrations of pesticides are analyzed providing the chemograms of the event. Hydrograms and chemograms are available for each storm event from April 2003 to September 2006. Corresponding hyetograms are provided by the MeteoFrance station located in the middle of the catchment.

The mean runoff per event is stable (mean: 4 L s^{-1} ; standard deviation: 0.9 L s^{-1}). The yearly maximal runoff value observed is largely varied and ranged from 19 to 127 L s^{-1}. The runoff coefficients calculated for the catchment are less than 4% throughout the 4 years. These low coefficients can be explained to the vineyard management practices which involve grass cover. Indeed, this practice was initially adopted for soil conservation and is expected to decrease surface runoff. Therefore, the mean volume generated during events was relatively low and ranged from 31 m^3 (2004) to95 m^3 (2006) with a maximum value of 250 m^3 (2006) (Table 2). The infiltration process is predominant during the rainfall events. However, pesticides in surface water represent regionally the main threat both for surface water and groundwater. Indeed, runoff produced on the vine growing area may rapidly flow towards downstream water bodies which are closely linked to the Rhenan aquifer.

2.4. The Runoff-Erosion LISEM Model

The Limburg Soil Erosion Model (LISEM) is a physically based hydrological and soil erosion model extensively described by De Roo et al. (1996). LISEM was one of the first examples of physically based model to be completely incorporated in the raster Geographical Information System PCRaster (Van Deursen, 1995). LISEM is an event-based model, i.e. only a single rainfall-runoff event can be simulated. Some processes as evaporation are neglected at this time scale. The model incorporated the following hydrological processes: rainfall, interception, surface storage in micro-depression, infiltration, vertical movement of water in the soil, overland flow, and channel flow. The erosion processes that can be include in the model are detachment by rainfall and throughfall, detachment by overland flow as well as transport capacity of the flow. The model had been applied in different hydrological contexts, in China and Belgium (Jetten et al., 2003), in Laos (Chaplot et al., 2005) and in Tanzania (Vigiak et al., 2006). These applications pointed out a good capability of LISEM to reproduce the hydrological behavior at the catchments’ outlet. Total discharge is generally better predicted than peak discharges and both are better predicted than sediment discharges.

2.5. Modeling the Hydrological Connectivity Using LISEM

The first modeling step is the data preparation. This step involves the extraction of most accurate digital elevation model (DEM) from the initial topographical data. The resolution chosen for the DEM is 2 m. This value appears as the better compromise between the accuracy to depict the landscape components, i.e. grass strips, roads and vineyard ranks, and the calculation limits of LISEM. This DEM extraction had been performed in the ArcGIS GIS software. Field-scale monitoring data were used to determine the values of Leaf Area Index, random roughness, saturated hydraulic conductivity, initial moisture content, porosity, average suction at the wetting front and soil depth for each land-use types (Table 1).

The second step concerns the LISEM calibration and validation on the Hohrain catchment. The calibration step was performed with the 26/04/2006 event. The Green & Ampt infiltration sub-model was applied directly with the parameter values observed at the field-scale without calibration. The manning’s *n* coefficients both on fields and roads are calibrated to fit the simulated hydrograms *versus* the observed hydrograms. The 09/04/2008 event was used to validate the capacity of LISEM to reproduce the runoff dynamic. The characteristics of these rainfall-runoff events are summarized in table 1.

Table 1. Characteristics of the two rainfall-runoff events used to calibrate and validate the LISEM model on the Hohrain catchment (Rouffach, Haut-Rhin, France).

		Rainfall characteristics			Runoff characteristics			
Step	Events	Depth (mm)	Duration (min)	Maximal intensity (mm/h)	Volume (m3)	Peak value (l/s)	Duration (min)	Runoff coefficient (%)
Calibration	26/04/2006	13.6	0h42	5.8	97	76	3h20	1.7
Validation	09/04/2008	13.8	7h18	8	150	14.4	7h48	2.5

These two events were selected among the 58 rainfall-runoff events based on both the volume and the runoff coefficient. Runoff coefficients were systematically lower than 4%. This can be explained by both the intensity of the rainfall event, i.e. any rainfall event is higher than 3-year frequency, and the increasing infiltration capacity of the catchment soil with the grassing inter-rows.

The third step is the characterization of both the active area and of the contributive fields. The pesticides applied on this area can be transferred downstream as a function of the level of connectivity that exists from the active zone up to the catchment outlet. The transfer can be stopped if landscape elements such as hedges, are located downstream and hinder the water flow or if elements such as grass strips or downstream part of field facilitate the infiltration. The first case was not taken into account in this work but can be performed by LISEM. The second case can be simulated with a spatially distributed model such as LISEM (Jetten et al., 2003).

3. RESULTS

3.1. Discharge Modeling

Table 2 summarizes the results of the calibration and validation steps. LISEM application using the monitoring values of soil characteristics and calibrated Manning's *n* values allowed to reproduce the hydrological dynamics of discharges with a volume difference lower than 18% for the validation event.

Table 2. Comparison of observed and simulated hydrological characteristics of the two studied runoff events at the Hohrain catchment (Rouffach, Haut-Rhin, France).

	Observed data				Simulated data			
Date of rainfall-runoff event	Volume (m^3)	Peak value (l/s)	Peak time (min)	Runoff coefficient (mm/h)	Volume (m^3)	Peak value (l/s)	Peak time (min)	Runoff coefficient (%)
26/04/2006	97	76	22	1.7	107	73	27	1.8
09/04/2008	150	14.4	326	2.5	125	17.4	330	2.1

3.2. Extraction of Active Versus Contributive Areas of Runoff

Figure 2 depicts simulated active areas with respect to runoff process associated with the 09/04/2008 event. If the active areas were directly connected to the road network, the fields were considered as contributive (Figure 2).

The active areas localized in the Western part of the catchment are covered by forest and pasture and are not connected to road area. Only 20% of the vineyard areas effectively contributed to the runoff. This is consistent with the direct runoff observation during two rainfall-runoff events (29/06/2005 and 29/06/2006), which were similar to the simulated events in terms of rainfall amount and discharge volume (Table 3).

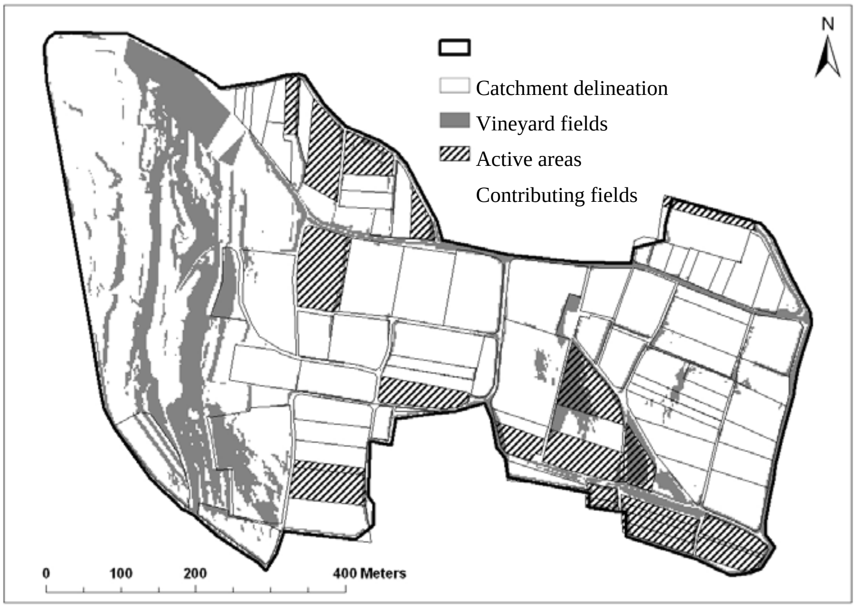

Figure 2. Location of the active and contributive areas simulating by LISEM in the Hohrain catchment (Rouffach, Haut-Rhin, France).

Table 3. Comparison of hydrological characteristics of both the two simulated events (26/04/2006 and 09/04/2008) and the two events with direct runoff observation (29/06/2005 and 29/06/2006) at the Hohrain catchment (Rouffach, Haut-Rhin, France).

Runoff events	Rainfall depth (mm)	Discharge (m^3)
29/06/2005	19.6	108
29/06/2006	13	140
26/04/2006	13.6	97
09/04/2008	13.8	150

The contributive part of the road network is also in good agreement with this observation.

4. DISCUSSION AND CONCLUSION

This study showed that a detailed integration of the connectivity at the catchment scale is crucial to distinguish the active areas, i.e. generating runoff, from areas that effectively contribute to the discharge at the outlet. A disconnected field, i.e. with no hydrological connectivity from field to catchment outlet, should not contribute to the pesticide loads at the catchment scale. Although only a low vineyard area is effectively contributive, the mean event concentrations of pesticides used on vineyard fields are high. For instance event mean glyphosate concentrations ranged from 0.2 to17.5 µg L^{-1} for the 58 runoff events. During the event of 09/04/2008, the mean concentration value for glyphosate was 42 µg L^{-1} and maximally reached 100 µg L^{-1}. For this event, a mean value of 360 µg L^{-1} has been measured at the outlet of the experimental plot. The results suggest that the pesticides concentration values at the catchment outlet only reflect a few number of contributive fields that displayed a high concentration of pesticide in the active zone.

The results also underscored the limit, especially for small catchment, of the Hydrological Response Unit (HRU) concept, i.e. the definition of the smallest part of a catchment with homogenous hydrological behavior, usually used in hydrological model such as SWAT (Holvoet et al., 2008). Consequently, both observed and simulated active areas were smaller than the areas of units obtained by crossing land use and soil type. It can be noted that the described methodology was specifically adapted to catchments in which surface runoff represents the main hydrological process explaining the discharge observed at the outlet. This method has to be adapted to take into account subsurface flow if necessary as described in Frey et al., (2009).

In conclusion, the following points have to be taken into account when assessing at the catchment scale critical source areas of pesticides losses:

- The more relevant water flow path within the catchment should be extracted and include landscape components which block, hinder or enhance the runoff flow, and the subsurface flow when required. The use of both high resolution topographical and direct observations data can substantially improve the water flow extraction.
- A fully distributed model should be used to take into account the spatial and temporal variability of hydrological processes within the catchment. A raster representation of landscape elements with an adapted resolution allows taking into account this variability. The limit of this raster approach is the size of the investigated catchment. The use of the HRU concept is an alternative for catchment with areas higher than 1 km².
- To associate the risk of pesticide transfer to a rainfall event return period, the contributive fields should be simulated according to the procedure described in this study for various rainfall events. Indeed, the active and contributive areas vary over time. According to the event discharge volume that has been generated at the outlet a catchment, the main objectives is to store and mitigate the pesticide loads while protecting downstream populations and goods.

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