An indicator approach for describing the spatial variability of artificial stream networks with regard to herbicide pollution in cultivated watersheds

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Abstract

Artificial stream networks play a major role in water and pollutant transfer within cultivated watersheds. Since the characteristics of these artificial stream network (e.g. width, vegetation cover, presence of sediments, etc.) are highly variable in space and in time, describing their variability appears as a prerequisite for assessing environmental risk of pollution at watershed scale. In this perspective an indicator approach is presented which includes three steps: (a) collecting properties of reach (i.e. elementary stream) along an artificial stream networks by means of a field and GIS-based approach, (b) deriving from these properties a set of quantitative indicators of hydrological and chemical processes involved in herbicide transfer, (c) classifying reaches in terms of their role in herbicide transfers on the basis of these indicators. The application of this method to three different watersheds located in France – Roujan watershed (South), La Morcille (East-Centre) and Le Cétras (North-West) – confirms that artificial stream networks of cultivated watersheds are highly spatially variable in regard to pollutant transfer. This spatial variability includes both variations between the watersheds and variations within the watersheds. Furthermore, the study reveals that the stream network properties can also be variable in time.

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1. Introduction

Artificial stream networks are important components of agricultural landscapes, especially in French intensively cultivated areas in which they have been traditionally used for draining excesses of water and/
or limiting erosion. Ditches constitute the main component of these networks but roads, paths and buried-pipes can also be encountered. As they link agricultural fields and receiving aquatic systems, artificial stream networks have several impacts on water and pollutant transfers within cultivated watersheds. They can accelerate water and pollutant transfers from the fields to the main stream draining the watershed (Carluer and de Marsily, 2004), redirect pollutants from surface water to neighbouring aquifers by re-infiltrations in ditches (Louchart et al., 2001, 2004), uptake and release phosphorus (Nguyen and Sukias, 2002; Barlow et al., 2003) or enhance mitigation of herbicides in presence of vegetation and sediments in ditches (Moore et al., 2001; Garon-Boucher et al., 2003; Margoum et al., 2001).

In spite of this recognized impact on water and pollutant transfers, the artificial stream network properties that may influence these transfers (e.g. network geometry, reach slope, covering nature of reach’s bed, bottom and edges texture and permeability, etc.) are not taken into account to define the environmental conditions used to calculate the current pesticide environmental risk indicators (Reus et al., 2002). Yet, these properties are expected to be highly variable in space and in time as they result from the interaction of many space–time–variable-factors such as relief, water-table level, land use, design objectives or maintenance strategies. Describing this variability appears therefore as a prerequisite to discriminate situations of contrasted risk level with respect to artificial stream network characteristics.

Up to now, the characteristics of artificial stream networks and their variability have received little attention. Some hydrological models (Moussa et al., 2002) consider explicitly the network geometry and reach slopes but few details are provided about how to collect these data and to obtain normalized characterization. Bouldin et al. (2004) quantitatively assessed ditch vegetation in view of ranking ditches for their ability to reduce excess nutrient, suspended solids and pesticides. They confirmed that the ditches can be highly variable with regard to this ability. However, they account only for one among the various roles that artificial stream network could play in pollutant transfers. Although a first attempt of describing artificial stream networks has been sketched out (Kao et al., 2002), it finally results that no generic method has been proposed until now to assess all the impacts of the variability of artificial stream networks on pollutant transfers. The aim of this paper is to fill this gap. The proposed indicator approach includes three steps, (a) collecting properties of reach (i.e. elementary stream) along an artificial stream networks by means of a field and GIS-based approach, (b) deriving from these properties a set of quantitative indicators of hydrological and chemical processes involved in herbicide transfer, (c) using these indicators to classify reaches in terms of their role in herbicide transfers on the basis of these indicators. This indicator approach is applied to three different watersheds located in France: Roujan watershed (South), La Morcille (East-Center) and Le Cétrais (North-West).

2. Method

2.1. General principles

The difficulty to characterize artificial stream networks with regard to pollutant transfer is two-fold. First, artificial stream networks are complex geographical objects that need to be carefully delimited and stratified before any characterization. Secondly, the role of an artificial stream network on pollutant transfer results from the complex interaction of several hydrological and hydro-bio-geo-chemical processes. These two problems are dealt successively in the following.

2.1.1. Dealing with geographical complexity

Artificial stream networks include the set of permanent ditches, canals, roads, path or pipes in which water issued from agricultural fields flows out to the main stream draining the watershed. It ends downstream where the natural main stream appears, i.e. where there is evidence of a pre-existing stream before human presence. To describe such a complex geographical object it is necessary to divide it into simpler objects, namely the reaches. Reaches are sections of an artificial stream network, which are considered as homogeneous for the descriptive parameters that will be defined further. Reach boundaries are either intersections with other reaches or intersections between reaches and field boundaries (Fig. 1), so that a given reach is edged on each of its side by a unique agricultural field. In some cases
where there is evidence of abrupt changes of the reach properties, a subdivision is introduced. This occurs in particular when a pipe connects two ditches (Fig. 1). Finally, the subdivision of artificial stream networks that is proposed here is more detailed than classical ones such as Strahler order (Strahler, 1964) that were defined for hydrological modeling purpose.

Vector GIS (Burrough, 1986) is the appropriate tool for representing numerically artificial stream networks and their individual components, the reaches. Vector layers can represent both the geometry of these geographical objects and the topology of reaches, i.e. the connectivity of reaches and the spatial relation between reaches and parcels. This allows to determine the position of a given reach within the network, e.g. establishing the list of upstream/downstream reaches (Fig. 1). GIS procedures can also be used for delineating the directly drained area of a reach, i.e. the area resulting from the difference between the watershed having as outlet the downstream extremity of the reach and the one having as outlet the upstream extremity (Fig. 1). Such procedures have already been used by Lagacherie et al. (1996) and Moussa et al. (2002).

2.1.2. Dealing with the complexity of herbicide transfer in artificial stream networks

The role of an artificial stream network on herbicide transfer results from the complex interaction of several hydrological and hydro-bio-geo-chemical processes. It would be therefore unrealistic to summarize this role by a unique indicator. The proposed alternative is to first define indicators accounting for each process taken individually. Each indicator is based on – and should conceptually represent – the knowledge that can be found in the literature about the considered process. They are quantitatively defined by means of mathematical formulas that combines a set of parameters characterizing each reach (e.g. width, sediment, vegetation rate, etc.). Therefore, these quantitative indicators provide a way of ranking individual reaches with regard to their potential role in the considered process. In this paper, three processes are considered because of their recognized influence on herbicide transfer, i.e. collection of herbicides from the directly drained area, conveyance of herbicides along the reach and retention of herbicides in the reach (Fig. 2).

The resulting quantitative process indicators are then further combined to classify reaches in terms of a more global behavior in herbicide transfer. They also involve a spatial aggregation in order to account for the position of each reach within the whole network.

This leads to propose a three steps approach for describing artificial stream networks:

- collecting reach characteristics regarding its potential role on pesticide transfer along an artificial stream network;
- calculating indicators of selected hydrological and chemical processes influencing herbicide transfer;
- classifying reaches with regard to their potential role in herbicide transfer and retention.

These steps are detailed in the following.

2.2. Collecting reach characteristics along an agricultural ditch network

Individual reaches are still too complex for being described easily with a set of unambiguous parameters. Therefore, the characterization of each reach has been done through six components, each component being separately described by a set of specific parameters. Fig. 3 shows these six components, namely reach section, reach bottom, left and right reach walls, left and right reach connections with neighboring fields.

Each component of a reach is described by a set of observable variables (Table 1) that are considered as relevant with regard to at least one of the considered hydrological or chemical processes. A great attention is paid to avoid ambiguities of description so that two different observers could converge to the same reach descriptions. Quantified observations (i.e., continuous variables) are largely privileged (Table 1), e.g., percent of sediment cover instead of low, medium, high sediment cover—and too global descriptive parameters—such as reach maintenance level—are avoided. Moreover, indications are given to characterize a reach as a whole from local representative observations (i.e., spatial integration). In most cases modes or means are determined (Table 1). However, in some cases, other forms of spatial integration (minimum or maximum) are privileged if they are more relevant for the process they aim to describe.

Since no data are currently available for estimating most of the reach characteristics presented before, a field survey is required for most of them (Table 1). However, a small number of reach characteristics can be estimated within GIS by using external source of data (Table 1). Reach length is calculated by the GIS topology builder from the digitized version of the reach network. Reach slope is calculated by dividing the difference in elevation between the two reach boundaries by the reach length, elevation at reach boundaries being interpolated from a Digital Elevation Model. In case of negative calculated slope (in flat areas where DEM is too imprecise), the reach slope is arbitrary fixed to the smallest value found in the watershed. The herbicide application area, i.e., the area which corresponds to the cultivated fields using herbicides that are drained by the reach is determined by overlaying in a GIS a land use map and the directly drained areas map (see Section 2.1.1).

2.3. Calculating indicators of hydrological-chemical processes influencing herbicide transfer

The aim of the proposed indicators of hydrological–chemical processes is to represent the behavior of reaches with regard to one of the processes involved in herbicide transfer (Section 2.1.2) so that reaches can be compared to each other within a watershed. We privileged indicators based on well-
known physical laws or on field experiments that can be derived from the easy-to-collect variables described in the previous section. In view to assess the applicability of such indicators, the simplifying hypothesis associated with each indicator are given explicitly. Indicators are presented in the following according to each hydrological–chemical process identified before.

2.3.1. Indicators of herbicide collection

The potentiality of a reach to collect herbicides is summarized by the Directly Drained Efficient Area (DDEA), which is calculated as follows:

\[ \text{DDEA} = \text{HAA} \times I \]  

(1)

with HAA is the herbicide application area (in ha) (Table 1) and \( I \) the interception coefficient. The interception coefficient \( I \) accounts for the ability of reach connections to intercept herbicide losses. It is determined by a Boolean rule (Fig. 4), which is based on experimental studies of herbicide interception (Madrigal et al., 2002).

2.3.2. Indicators of transfer of herbicide within a reach

The transfer of herbicide within a reach is summarized by the mean velocity that is calculated by the Manning formula (Chow et al., 1988):

\[ V = K S^{0.5} R^{2/3} \]  

(2)

with \( V \) is the velocity in m/s, \( K \) the coefficient of roughness, \( S \) the reach slope gradient in m/m, and \( R \) the hydraulic radius in m.

Dissolved herbicide transport is directly related to the mean water velocity in reaches. It is also meaningful for herbicides in adsorbed phase since water speed plays a major role in the sediment transfer.

The application of the Manning formula requires some hypothesis concerning the parameters \( K \) and \( R \).
$K$ is a non-dimensional coefficient which is determined from qualitative descriptions of the reach bottom and the reach walls using rules initially established by Manning for canals (Chow et al., 1988). However, the canal classes that were defined for estimating $K$ values were found too large for accounting for the observed variability of artificial streams of elementary watersheds. Consequently, new intermediate classes had to be created with intermediate values of $K$ (Table 2). In order to handle a unique value of $V$ for further comparisons, $V$ was calculated from the median value of the intervals of $K$ provided in Table 2.

The hydraulic radius $R$ is defined as the ratio between the wet surface and the wet perimeter. It thus depends on the reach geometry (lower and upper width) but also from the water height in the reach (Chow et al., 1988). Although this last parameter is highly variable according to the amount of rainfall, a theoretical value has to be fixed to calculate $R$. The water height was then fixed at 5 cm, which ensures the applicability of the Manning formula to each reach of the watershed.

The above described determination of the velocity was also extended to roads and paths, considered here as shallow ditches (height fixed arbitrarily at 5 cm).
2.3.3. Indicator of herbicide retention within reach

The herbicide retention power (HRP) accounts for the capacity of a reach to adsorb herbicides on its bottom and on its walls. Some experimental studies (Crum and Broks, 1994; Margoum et al., 2001) have shown that sediments, dead vegetation and living vegetation in ditches could retain herbicide. A retention indicator that takes into account the unequal retention capacity of these three materials has been established (Margoum et al., 2001). It will be reused in this study:

\[
HRP = 0.5S + LV + 2DV
\]

with HRP the herbicide retention power (%), \(S\) the relative cover in sediments (%), LV the relative cover in living vegetation (%), DV the relative cover in dead vegetation (%).

The HRP indicator does not take into account the other processes potentially involved in herbicide dissipation such as biotic and abiotic degradations and further releases of herbicides. However, it seems reasonable to suppose that the variables used for establish HRP are not totally disconnected from these processes. Anyway, this indicator appears as more relevant to compare herbicide retention during a single rain event than to globally estimate retention at the seasonal scale.

2.4. Classifying reaches with regard to their role in herbicide transfer

The previously proposed indicators can be combined into more global ones for summarizing the role of reach in herbicide transfer. One of this global indicator is presented here as an example. The main difference with the previous ones is that it is explicitly defined as qualitative since (i) The three elementary process indicators that are combined, although quantitative, does not deal with volumes of herbicides and mainly account for a hierarchy between the reaches, (ii) interactions between processes are insufficiently known, (iii) the static nature of the indicators does not allow to represent quantitatively dynamic interactions.

The global proposed indicator classifies reaches into three classes:

- class A: weak potential and actual influence on herbicide transfer, i.e. small amount of received herbicide whatever the retention ability;
- class B: strong potential influence on herbicide transfer but weak actual one, i.e. large amount of received herbicide and weak retention ability;
- class C: strong actual influence on herbicide transfer, i.e. large amount of received herbicide and strong retention ability.

In practical terms, class B reaches are those where the retention potential must be preferentially enhanced whereas class C reaches are those that required to be protected for conserving this potential.

Allocation of reach into class A, B or C requires to define what is considered as (i) “weak/strong retention ability” and as (ii) “weak/strong amount of received herbicide”. These two problems are addressed in the following. Then the allocation of reaches to classes A–C will be finally presented.

2.4.1. Characterizing the effective reach herbicide retention ability

According to the few experimental results presented in the literature (Moore et al., 2001; Margoum...
et al., 2001), herbicide retention in reach must be considered as maximum in situations characterized by high amount of materials able to mitigate herbicide and high herbicide-material contact duration, i.e. low herbicide transfer speed. This can be represented by combining the $V$ and HRP indicators presented respectively in Sections 2.3.2 and 2.3.3. As these indicators are only significant for ranking reaches according to a given process, the selected method of combination will be a rank combination as shown in Table 3, the classes “low”, “medium” and “high” being defined from the distributions of values of indicators HRP and $V$ so that they include the same number of individuals. A new qualitative indicator is thus defined: effective reach herbicide retention ability (ERHRA).

### 2.4.2. Characterizing the amount of received herbicide

The amount of herbicide received by a given reach depends on (i) the surface of the herbicide application area that is drained by the reach or by the upstream network, eventually diminished by reach connection intercepts and (ii) the ability of the upstream network to retain herbicides before the reach. The former property can be summarized by summing along the upstream network the indicator DDEA presented in Section 2.3.1.

\[
TDEA = DDEA_0 + \sum_{i=1}^{n} DDEA_i
\]

with TDEA is the total drained efficient area at the outlet of reach 0 (ha), DDEA$_0$ the directly drained efficient area by reach 0 (ha), DDEA$_i$ the directly drained efficient area of the $i$th upstream reach, and $n$ the number of upstream reaches.

The latter property will be calculated by spatially integrating the ERHRA indicators along the upstream network according to the following formula:

\[
UHRA = \frac{\sum_{i=1}^{n} l_i ERHRA_i}{\sum_{i=1}^{n} l_i}
\]

with UHRA is the upstream herbicide retention ability, ERHRA$_i$ the effective reach herbicide retention ability of reach $i$, and $l_i$ the length of the $i$th upstream reach.

One must note that calculating TDEA and UHRA requires a prior representation of reach network topology as stated in Section 2.1.

TDEA and UHRA can be then combined in view to evaluate qualitatively an amount of received herbicide (ARH). As for defining ERHRA (see Section 2.4.1 above), a rank combination of indicators appears as the best solution for differentiating reaches with regard to this new represented property. The same approach as shown in Table 3 is then applied, TDEA and UHRA playing the role of HRP and $V$, respectively.

### 2.4.3. Final allocation to herbicide transfer reach classes

Allocation of reaches to classes describing their effective/potential influence on herbicide transfer is based on a combination of the two qualitative indicators previously calculated which take into account the definition of classes presented earlier (Table 4).

<table>
<thead>
<tr>
<th>ERHRA</th>
<th>ARH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
</tr>
</tbody>
</table>

Table 4
Combination of effective reach herbicide retention ability (ERHRA) and of amount of received herbicide (ARH) to establish classes (A, B, or C) describing the potential/effective influence of reaches on herbicide transfer
3. Studied watersheds and collected data

3.1. Studied watersheds and their agricultural reach networks

The studied watersheds of Roujan, La Morcille and le Cétrais (Fig. 5) are experimental watersheds in which a number of studies have been carried out by the three research teams associated in this paper, e.g. Louchart et al. (2001) for Roujan, Gouy et al. (1998) for La Morcille and Kao et al. (2002) for le Cétrais. A full description of these watersheds is available in the cited papers. Only the main characteristics of the studied watersheds are presented in Table 5.

The three watersheds have similar cumulative lengths of stream networks but contrasting densities of stream networks. The Cétrais watershed differs strongly from the two others, particularly in terms of agrosystem, and herbicide type. Roujan and Cétrais show differences in relief, soil, percentages in weeded crops (here vineyard) and viticulture systems and practices.

3.2. Data

3.2.1. GIS data

Two types of GIS data were required to characterize the stream networks of the studied watersheds. The first is the digitized version of the agricultural parcels with their associated land-use. To obtain this in the three watersheds, the contours of the parcels were first digitized from cadastre maps. Then, aerial photographs were used for eliminating virtual cadastre parcel boundaries and for determining the land uses of each parcels. Further verifications and corrections were made during the field surveys of stream networks.

The second type of GIS data is digital elevation models (DEM), which were obtained from different sources of data according to the studied watershed. In Roujan watershed, a 1 m resolution DEM was derived from a triangle irregular network that was built from a dense sampling of elevation points (17 880 points). In La Morcille watershed, a 5 m resolution DEM was calculated by interpolating contour elevation of the 1:25 000 topographical map of IGN (French Institute of Geography). In le Cétrais a similar DEM as the one of La Morcille was obtained by interpolating the initial

Table 5

<table>
<thead>
<tr>
<th></th>
<th>Roujan</th>
<th>La Morcille</th>
<th>Cétrais</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studied area (ha)</td>
<td>91</td>
<td>41</td>
<td>460</td>
</tr>
<tr>
<td>Average slope gradient (%)</td>
<td>7</td>
<td>25</td>
<td>3.3</td>
</tr>
<tr>
<td>Soil</td>
<td>Calcosols, chromic cambisol</td>
<td>Brunisols</td>
<td>Gleyic luvisols</td>
</tr>
<tr>
<td>Climate</td>
<td>Humid mediterranean</td>
<td>Semi continental</td>
<td>Oceanic</td>
</tr>
<tr>
<td>Dominant crop</td>
<td>Vineyard</td>
<td>Vineyard</td>
<td>Maize, wheat, pasture</td>
</tr>
<tr>
<td>Percentage of weeded crops</td>
<td>71</td>
<td>88</td>
<td>66</td>
</tr>
<tr>
<td>Main herbicide</td>
<td>Diuron</td>
<td>Diuron</td>
<td>Isoproturon</td>
</tr>
<tr>
<td>Cumulative length of stream network (km)</td>
<td>12.5</td>
<td>12.3</td>
<td>12.0</td>
</tr>
<tr>
<td>Density of stream network (m/ha)</td>
<td>137</td>
<td>300</td>
<td>26</td>
</tr>
</tbody>
</table>

Fig. 5. The three studied watersheds (grey areas) and their artificial stream networks (black lines).
25 m resolution DEM provided by the IGN BD Alti™. All the functions required to build these DEMs were found in the TIN module of Arc/Info version 7.0.1.

3.2.2. Field data

The stream networks of the three watersheds were surveyed following the method presented in Section 2.2. A total of 36.263 km of stream networks were characterized in spring 2002 (La Morcille) and 2003 (Roujan, Cétrais and complements in la Morcille) with an average survey speed of 1.225 km per day. Besides, two earlier surveys on the Roujan watershed which were undertaken in the adaptation phase of the survey method are also considered here to assess the robustness of field observations and temporal variability: (a) a first exhaustive survey in April 2000 and (b) a second survey in April 2001 of 65 twice-described or thrice-described reaches that provide 98 couples of differing descriptions of a same reach.

3.3. Computing process indicators and reach classes

The process indicators and the reach classes were determined over the three stream networks following the methods presented in Sections 2.3 and 2.4, respectively. The calculations were made in Microsoft Excel™ tables that were associated with Arc.View™ geographical layers of stream networks. Spatial function for determining upstream or downstream stream networks or directly drained area (Fig. 1) were all programmed in GIS ARC/INFO™ and ARC/View™.

4. Results

The results presented hereafter concern the three steps of the indicator approach, i.e. the determination of reach characteristics (Section 2.2), the calculation of indicators of hydrological and hydrochemical processes (Section 2.3) and the classification of reaches with regard to their role in herbicide transfer (Section 2.4).

4.1. Variability of individual reach properties

Two examples of reach characteristics will be examined, namely reach upper width and living vegetation cover of reach bottom. These two characteristics were selected because (i) they represent the two main types of characteristic determinations of the field survey, i.e. measurement (for reach width) and expert judgement (for living vegetation cover) (ii) they differ by their factors of variation, and (iii) their definitions have not been noticeably changed since the earlier surveys, which allows temporal comparisons.

4.1.1. Robustness of field parameters estimation and temporal variability

In order to test the robustness of the field determination of reach characteristics – i.e. the absence of a surveyor bias – mean, minimum and maximum differences of upper width and living vegetation cover of the whole reach were calculated from the 98 couples of differing descriptions of a same reach in Roujan. Temporal variability was then estimated by calculating the mean difference and the mean of absolute values of differences over the reaches of the Roujan watersheds that were successively surveyed in April 2000 and in March–April 2002. Invariant reaches such as pipes and road were not considered for this temporal comparison. Besides, ditches with upper width less than 2 m were also excluded since they were not represented in the 98 couples of differing descriptions from which references of robustness were established. Finally, sets of 147 and 170, 2000–2002-surveyed reaches were used for comparing upper width and living vegetation cover respectively.

Results (Table 6) from the 98 couples of differing descriptions of a same reach show low but not negligible differences for the two parameters with great dispersions as shown by minimum versus maximum values. These differences could be interpreted either as determinations made at different locations within the reach or as the consequences of imprecise measurements or observations at similar locations.

Comparisons between 2000 and 2002 reach characteristics (Table 6) show contrasting results according to the considered characteristic. The mean absolute difference between 2000 and 2002 determinations of reach remains similar to the mean difference between surveyors (Table 6), which reveals that no significant changes of reach width have occurred within the 2000–2002 period. Conversely,
the mean absolute difference between 2000 and 2002 determinations of living vegetation is significantly higher than the one between surveyors. This means that this characteristic is subject to temporal variations. In this case, the negative mean difference shows that the change is oriented toward more reach maintenance in 2002 than in 2000.

4.1.2. Spatial variability

Spatial variability was quantitatively evaluated by calculating for the two studied characteristics, i.e. reach lower width and living vegetation cover of reach bottom, and for the three studied watersheds the two following statistical indicators:

\[
LWM(c) = \frac{\sum_{i=1}^{n} l_i c_i}{\sum_{i=1}^{n} l_i}
\]

\[
LWSD(c) = \sqrt{\frac{\sum_{i=1}^{n} l_i (c_i - LWM)^2}{\sum_{i=1}^{n} l_i}}
\]

with \(LWM(c)\) is the length-weighted mean of reach characteristic \(c\), \(LWSD(c)\) the length-weighted standard deviation of reach characteristic \(c\), \(l_i\) the length of reach \(i\), \(c_i\) the characteristic \(c\) of reach \(i\), and \(n\) the number of reaches in the watershed.

Table 7 shows the length-weighted means (LWM) and the length-weighted standard deviation (LWSD) of the reach lower width and of the living vegetation cover that were calculated over the three studied watersheds. They reveal a high spatial variability of the lower width, both between (LWMs ranging from 0.34 and 2.06 m) and within these watersheds (LWSDs from 0.35 to 2.28 m). The Roujan watershed has the lowest lower-width-LWM since its stream network is mainly made of small-sized vinegrower-made ditches (Fig. 6a) whereas the significative presence of paths in La Morcille and the predominance of large ditches within the Cétrais watershed result in higher mean reach widths. The most variable stream networks are the Morcille and the Cétrais watersheds whereas the clear dominance of the vinegrower-made ditches within the stream network of Roujan leads to a lower variability of the lower width.

The studied watersheds differ also strongly to each other with regard to the living vegetation cover (Table 7). The lowest values of living vegetation cover LWM and LWSD are registered in la Morcille where the vine-growers regularly clean the stream network in order to limit erosion in this high quality wine production watershed. Conversely, Le Cétrais has the highest mean vegetation cover and the highest corresponding within-watershed variability, which indicates a much less maintained stream network. Roujan is an intermediate situation where the maintenance of the stream network for limiting the impact of Mediterranean rainfalls on erosion is also conducted, although it is neither as exhaustive nor frequent as in La Morcille.

### Table 6

| Variations of reach characteristics values with the surveyors and with time |
|------------------------------|-----------------|-----------------|
|                              | Mean | Min | Max | Bias | Mean |
| Upper width                  | 17 cm | 0 cm | 70 cm | -5 cm | 22 cm |
| Living vegetation cover      | 9% | 0 | 70% | -17% | 23% |

| Table 7 |
|---|---|---|
| Spatial variability of reach characteristics in the three studied watersheds |
| Reach characteristics | Statistics | Roujan | Morcille | Cétrais |
| Lower width | LWM* | 0.34 m | 2.06 m | 1.03 m |
|             | LWSD* | 0.35 m | 2.28 m | 0.86 m |
| Living vegetation cover | LWM | 19% | 7% | 22% |
|             | LWSD | 23% | 22% | 33% |

*a* Length-weighted mean of the reach characteristics.

*b* Length-weighted standard deviation of the reach characteristics.
4.2. Spatial variability of process indicators

The three indicators of hydrological-chemical process that were presented in Section 2.3 were calculated from the reach characteristics collected over the three studied agricultural stream networks. The statistical indicators LWM and LWSD – see formulae (6) and (7) – were used to examine variations both between and within watersheds (Table 8). In the case of DDEA, LWM and LWSD are calculated over the set of collecting reaches i.e. the ones that were found to be connected to a draining area. Percentages of such reaches relatively to the whole stream networks and the sums of the DDEAs over the whole watershed are also indicated in Table 8.

The Cétrais watershed shows a significantly lower length-weighed mean velocity (LWM) than the two others (Table 8). This is interpreted as the result of a smoother relief. However, the relation between relief and mean velocities is not linear since differences of velocities between Roujan and la Morcille are small, whereas la Morcille includes steeper slopes. In the former, the greater velocities due to steep slopes may be compensated by a denser stream network (Table 5) that includes a lot of cross slope reaches for intercepting the run-off. Other properties of the stream networks (e.g. vegetation cover, reach width, etc.) could also play a role in altering the linearity of the relation between relief and mean velocities. Besides, it is worth to notice the very high within-watershed variability of velocity as measured by the LWSD (Table 8) for all the watersheds.

The sums of the directly drained efficient areas (DDEA) over the watershed (Table 8) appear very close (Roujan) or equal (la Morcille, Cétrais) to the weeded crop areas (Table 5). This means for all the studied watersheds a weak ability of reach connections to intercept herbicide losses as measured by I coefficient (Eq. (1)). As expected, the DDEA length-weighed means (Table 8) vary according to the density of the watershed stream networks (Table 5). The smaller proportion of weeded crop in the Roujan watershed has also a depressive effect on DDEA length-weighed means. Besides, all the watersheds are characterized by a very high variability of reaches in terms of DDEA. This is revealed by, first, a significant part of the stream network that do not collect any herbicide (first line of Table 8) and, second, a high DDEA length-weighed standard deviations whatever the watershed.

The variation of the herbicide retention power (HRP) between the three watersheds looks very similar to the one of living vegetation cover as shown in Table 8, although the differences between watersheds are smoothed. As for living vegetation cover, differences of maintenance strategies between watersheds can be evoked for explaining HRP variations since the two other reach characteristics that are involved in the calculation of HRP – namely dead vegetation cover and sediment cover – are also related to stream network maintenance. As for the two previous indicators (DDEA and V), a great within-watershed variability is identified (LWSD in Table 8) with noticeable differences between watersheds, la Morcille watershed being the less variable.

4.3. Spatial distribution of herbicide transfer reach classes

The herbicide transfer reach classes were determined in the three studied watersheds according to the method presented in Section 2.4. As the classes are

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Statistics</th>
<th>Roujan</th>
<th>Morcille</th>
<th>Cétrais</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directly drained efficient area (DDEA)</td>
<td>% Collecting reaches</td>
<td>51</td>
<td>48</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Sum (% total area)</td>
<td>60</td>
<td>84</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>LWM(^a)</td>
<td>4.2 ha</td>
<td>3.2 ha</td>
<td>9.8 ha</td>
</tr>
<tr>
<td></td>
<td>LWSD(^b)</td>
<td>6.2 ha</td>
<td>4.7 ha</td>
<td>19.6 ha</td>
</tr>
<tr>
<td>Velocity (V)</td>
<td>LWM</td>
<td>0.8 m/s</td>
<td>0.9 m/s</td>
<td>0.02 m/s</td>
</tr>
<tr>
<td></td>
<td>LWSD</td>
<td>1.1 m/s</td>
<td>2.1 m/s</td>
<td>0.8 m/s</td>
</tr>
<tr>
<td>Herbicide retention power (HRP)</td>
<td>LWM</td>
<td>62%</td>
<td>56%</td>
<td>74%</td>
</tr>
<tr>
<td></td>
<td>LWSD</td>
<td>54%</td>
<td>34%</td>
<td>125%</td>
</tr>
</tbody>
</table>

\(^a\) Length-weighted mean of the indicator.
\(^b\) Length-weighted standard deviation of the indicator.
based on rank combinations that were defined separately for each studied watersheds, only the within-watershed distributions of such classes are to be examined, the comparisons between watersheds being meaningless. Fig. 6a–c shows these distributions in the watersheds of Roujan, Morcille and Cétrais respectively. In the Roujan and Cétrais watersheds, the reaches having the strongest potential influence on herbicide transfer (class B or C) are concentrated in the lower part of the watersheds whereas in the Morcille watersheds, upstream intercepting reaches are also in class B and C. The majority of these reaches (80 over 117 in Roujan, 82 over 116 in La Morcille and 75 over 83 in le Cétrais) has still a weak retention ability (class B) which means that the global ability of the stream network could be ameliorated by an appropriate maintenance strategy for these reaches (e.g. grassed ditches).

5. Conclusions

To account for the role of artificial stream networks in transferring herbicides from agricultural fields to watershed outlets, an indicator approach was proposed in this paper. This approach deals with the geographical complexity of agricultural reach networks and with the fragmented knowledge about herbicide transfer through these networks. Three steps were identified. First, a normalized and generic method was elaborated for collecting individual reach properties in relation with herbicide transfer. This method associates (i) field surveys supported by a glossary of properties, a field manual and a database registration, (ii) collection of existing data (digital elevation model, digitized cover of land parcels), and (iii) GIS procedures. Second, a set of quantitative, physically or experimentally based indicators were derived from the previous properties. They aim to account for each considered processes, i.e. herbicide collection, herbicide conveyance along the reach and herbicide retention within the reach. Finally, these quantitative indicators are spatially and qualitatively combined in view to classify reaches with regard to their global behavior in herbicide transfer. The method was designed, improved and tested on three different elementary watersheds distributed over the French territory.

The application of the method reveals a high spatial variability of reach properties whatever the studied elementary watersheds. This consequently yields a high spatial variability of hydrological/chemical process indicators and, finally, strong differences between reaches in term of their potential role in herbicide transfer. At a broader scale, differences between the stream networks of the three studied watershed are also identified. Besides, a test of the temporal variability of two key reach properties shows that this aspect must not be neglected in future surveys since reach properties can be modified by climatic conditions and maintenance work.

However, the proposed approach must be substantially ameliorated before being considered as a real support for decision-making. The first problem is that these improved indicators are, by essence, not time-dependent and thus cannot take into account the dynamic nature of herbicide transfer. This however can be partially overcome from the proposed approach since the hypothesis associated with indicators (e.g. water height in reach) can be set as variable to yield a set of indicators that could more precisely account for differing climatic periods. The second problem is that
the knowledge about herbicide dissipation along a reach is still too fragmentary to derive more relevant indicators. Further processes that were not taken into account in this study (e.g. sun or microbial degradation of herbicides, reach to/from water-table water transfer) or interactions between processes need further experimentation and modeling for being represented through quantitative indicators. The third problem is that the herbicide transfer reach classes are defined only from statistically based rank combinations, thus not defined from observations of actual behaviors with regard to herbicide transfer. To give more significance to these classes, it would be necessary to define their boundary from a set of field measurements of herbicides losses at the reach level (e.g. Moore et al., 2001). Another margin of progress lays in a better assessment of the spatial variability of reach properties including mathematical representation of the structure of the spatial variability over reaches network (Bailly et al., in press) and identification of the underlying physical processes and human decisions that govern the spatio-temporal variability of reach properties.

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