Environmental Management (2009) 43:921–935
DOI 10.1007/s00267-008-9244-x

ENVIRONMENTAL ASSESSMENT

Framework and Tools for Agricultural Landscape Assessment Relating to Water Quality Protection

Chantal Gascuel-Odoux · Florence Massa · Patrick Durand · Philippe Merot · Olivier Troccaz · Jacques Baudry · Claudine Thenail

Received: 22 October 2007 / Accepted: 3 December 2008 / Published online: 14 February 2009

Abstract While many scientific studies show the influence of agricultural landscape patterns on water cycle and water quality, only a few of these have proposed scientifically based and operational methods to improve water management. Territ'eau is a framework developed to adapt agricultural landscapes to water quality protection, using components such as farmers' fields, seminatural areas, and human infrastructures, which can act as sources, sinks, or buffers on water quality. This framework allows us to delimit active areas contributing to water quality, defined by the following three characteristics: (i) the dominant hydrological processes and their flow pathways, (ii) the characteristics of each considered pollutant, and (iii) the main landscape features. These areas are delineated by analyzing the flow connectivity from the stream to the croplands, by assessing the buffer functions of seminatural areas according to their flow pathways. Hence, this framework allows us to identify functional seminatural areas in terms of water quality and assess their limits and functions; it helps in proposing different approaches for changing agricultural landscape, acting on agricultural practices or systems, and/or conserving or rebuilding seminatural areas in controversial landscapes. Finally, it allows us to objectivize the functions of the landscape components, for adapting these components to new environmental constraints.

Keywords Agricultural landscape · Catchment · Management · Landscape features · Scores · Hydrology · Water quality · Stream water protection

C. Gascuel-Odoux (✉)
INRA, Agrocampus Ouest, UMR 1069, Soil Agro and HydroSystem, 65 Route de Saint-Brieuc, CS 84215, 35042 Rennes Cedex, France
e-mail: chantal.gascuel@rennes.inra.fr

C. Gascuel-Odoux · P. Durand · P. Merot
INRA, UMR 1069, Soil Agro and HydroSystem, 35000 Rennes, France

C. Gascuel-Odoux · P. Durand · P. Merot
Agrocampus Ouest, UMR 1069, Soil Agro and HydroSystem, 35000 Rennes, France

F. Massa
Chambres d'Agriculture de Bretagne, Maison de l'Agriculture, 35000 Rennes, France

O. Troccaz
Université de Rennes 1, CNRS, UMR ECOBIO, 35000 Rennes, France

J. Baudry · C. Thenail
INRA, UR 980, SAD-Paysage, 35000 Rennes, France

Agriculture is changing. While its primary purpose is the production of food and raw materials, farmers intend to be recognized as major managers of the rural landscape, particularly in areas where land is multifunctional. More generally, to be credible faced with other end uses, agriculture has to clearly and effectively demonstrate the control of its impact on the environment. From this perspective, water is a key resource having an individual and collective heritage value. Water quality can be easily integrated in a catchment area, and major issues such as the health of aquatic ecosystems and drinking water resources are the concern of everyone. In Europe, the regulation of agricultural landscape management in relation to water quality is a consequence of regional and European policies. Nonetheless, local regulations are also needed because of the human and environmental specificities of each community. From this point of view, it is necessary to identify and gain knowledge of landscape features and their functions as the starting point for common appropriation and management by end users.

Agricultural landscapes are made up of various features related to many environmental and human factors. Such landscapes are structured by a mosaic of farmers' fields, seminatural areas, and human infrastructures (Baudry 1997; Marshall and Moonen 2002). The spatial patterns of fields and crops vary over time according to the management of cropping systems and the farm-scale allocation of land use. The numerous technical operations of farmers contribute to changing the state of the vegetation cover and topsoil conditions, which hence influence flow pathways (Souchère and others 1998; Joannon and others 2006). Seminatural areas are composed of surface features, such as wood plots, set-aside fields, and riparian wetlands, and linear features, such as streams, field margins, and hedgerows. These seminatural areas are of a small extent and generally absent from regional or national environmental inventories (Merot and others 2006). Artificial infrastructures are superimposed on these features, mainly comprising ditches, roads, and human habitats, which are more or less connected to one another so they form surface and linear manmade networks.

All these features have an effect on catchment hydrology, erosion, and water quality. They can modify flow pathways and hydrological and hydrochemical functioning. These changes are described in numerous studies that assess the effects of landscape features on water quality (Merot 1999; Dorioz and others 2006). The concept of buffer capacity has been used to quantify this effect. This concept is defined as the ratio between pollutant input and pollutant output but remains rather inapplicable while these values are difficult to quantify, and this concept does not consider storage, side effects, or temporal delay (Viaud and others 2004; Dosskey 2002). Although the factors contributing to the buffer effect of an agricultural landscape are better and better known, quantification of the buffer capacity of each landscape element and, moreover, of the overall catchment remains difficult, and operational tools are needed to develop reasonable management of the agricultural landscape for protecting water (van Lanen and Demuth 2002). These issues require a new framework and tools addressing the complexity of agricultural landscapes and overcoming the difficulty of identifying the influence of each factor on water quality (Burt 2001).

Two main approaches have been developed to evaluate the effect of agricultural landscape features on water quality. The first one is based on transport modeling and generally focuses on a particular category of landscape element or pollutant. Among the many different models and their applications to evaluation of landscape features, we can cite the following: SWAT (Neitsch and others 2002), largely used to differentiate sites, pollutants, and landscape features (Ouyang and others 2008; Wang and others 2008); TNT (topographic-based nitrogen transfer and transformation model), used to assess the effect of riparian wetlands (Beaujouan and others 2001), agricultural practices (Beaujouan and others 2002), and hedgerows (Viaud and others 2005) on discharge and/or nitrate fate; STREAM (sealing and transfer by runoff and erosion related to agricultural management) (Cerdan and others 2001; Joannon and others 2006) and LISEM (Limburg soil erosion model) (de Roo and others 1996), both used to assess the effect of agricultural practices on erosion; and SACADEAU (Cordier and others 2005; Tortrat 2005), used to assess the effect of buffer zones and agricultural practices on herbicide fate. Despite a real improvement in pollutant transport modeling to integrate the complexity of agricultural landscapes, the models cannot predict pollutant fate in stream waters on any given catchment for operational purposes: the required data are not generally available, the landscape structures and functions are simplified, and modeling remains a task for specialists. Thus, the results of modeling cannot be entirely convincing for end users (Pilkey and Pilkey-Jarvis 2007). A second approach based on indicators has been proposed as an alternative to evaluating the risk of water pollution. Several indicators, such as pesticide indicators (Reus and others 2002; Devillers and others 2005) and nitrogen and phosphorus indicators (Heathwaite and others 2000, 2003), have been developed. These operational tools generally focus on farmers' fields, ignoring other landscape features. Despite a real convergence between models and indicators (Rao and others 2000), the models are still remote from operational issues, while the indicators are often controversial because they fail to capture the complexity and functioning of agricultural landscapes.

This study presents the Territ'eau framework and some of its incorporated tools. First, it is intended to help stakeholders assess the functions of the different features of an agricultural landscape in terms of water quality; second, it aims to build up major recommendations for the management of such landscapes in relation to water quality. We give here a summary presentation, detailing, illustrating, and discussing the major contributions using examples from different agricultural catchments located in western Brittany, France.

Overview of the Territ'eau Framework

Territ'eau is an operational framework dedicated to medium-size catchments (10–100 km^2) where stream waters are degraded by diffuse agricultural pollution and where remediation operations are planned. The territory is defined here as a study area that can be appropriated in a material or symbolic way by different stakeholders such as community leaders, farmers, fishermen, tourists, lay people, and Environmental NGOs. The starting point is a global characterization of the main human and environmental components of this territory, which allows us to define the specifications of the required diagnosis. This diagnosis is carried out based on regional databases and detailed field observations on the agricultural landscape, including fields, field margins, and seminatural and stream-bordering areas. In carrying out such a diagnosis, this framework promotes the participation of the inhabitants of the territory such as farmers, community staff, and the wider public.

This framework is described in a handbook similar to the EPA's handbook (2008), in simple vocabulary and an attractive form, but with numeric support (http://agro-transfert-bretagne.univ-rennes1.fr/Territ_eau/accueil.asp). It is summarized by Massa and others (2008). The hydrochemical functioning of the catchment and the effect of landscape features on the water quality are described exhaustively, as well as the method developed to carry out a diagnosis and recommendations for the catchment. The Territ'eau framework is based on a threefold principle. *The first principle is to focus on the main issues and constraints of the study area in relation to water quality*, i.e., the most important pollutants, the specific landscape features. They allow us to define the landscape diagnosis specifications (Fig. 1). Key contributing areas are determined by a bottom-up spatial strategy, which starts from the stream and progressively investigates the upslope areas. In this way, pollutant fate scores are not exhaustively calculated on the catchment but only on key contributing areas (Fig. 1), and thus the management of the catchment is focused on these areas.

The second principle is that the key contributing areas of the catchment are built from three types of information: (i) the hydrological functioning of the catchment, (ii) the characteristics of the pollutants, mainly related to their mobility and biochemical reactivity, and (iii) the main landscape features that can act on the pollutant fate. The information is used to assess water and pollutant flow connectivity and chemical reactivity from field to field along water and pollutant flow pathways, and to assess where the pollutant sources are and where they can be retained or transformed by structures acting as buffer zones. Four types of hydrological contributing areas are defined (Fig. 2)—(i) the functional hydrosystem including streams as well as actively flowing ditches; (ii) saturated overland areas delineated by wetlands; (iii) unsaturated overland flow areas delineated by slope conditions and, as commonly found in European landscapes, field limits such as earth banks; and (iv) areas where the water table is close to the soil surface, characterized by quick subsurface flow, delineated by hydromorphic soil features—as well as (v) the whole catchment, dominated by low subsurface flow and easily delineated from the DEM (digital elevation model). This hydrological typology has been used in the past (Peschke and others 1999; Scherrer and Naef 2003; Leu and others 2004; Schmocker-Fackel, 2004). Crossing these types of areas and the pollutant characteristics, mainly mobility and chemical reactivity, allows us to delineate key contributing areas specifically defined for each pollutant (Fig. 2). While the whole catchment concerns highly mobile pollutants with a long residence time such as nitrates, the less extensive areas concern pollutants with a low mobility or a high biodegradability such as pesticides. The quick subsurface flow area is assumed to contribute to the herbicide fate, and the overland flow area to the phosphorus fate. In a functional hydrosystem, we only take into account erosion processes along river banks as a potential source of suspended sediments. In contrast

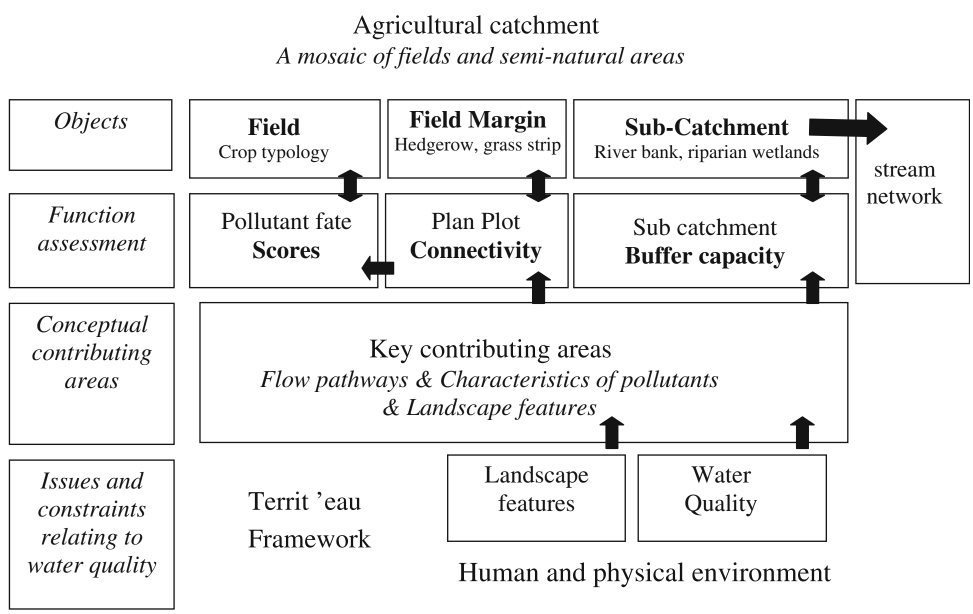

Fig. 1 Diagram of the Territ'eau framework

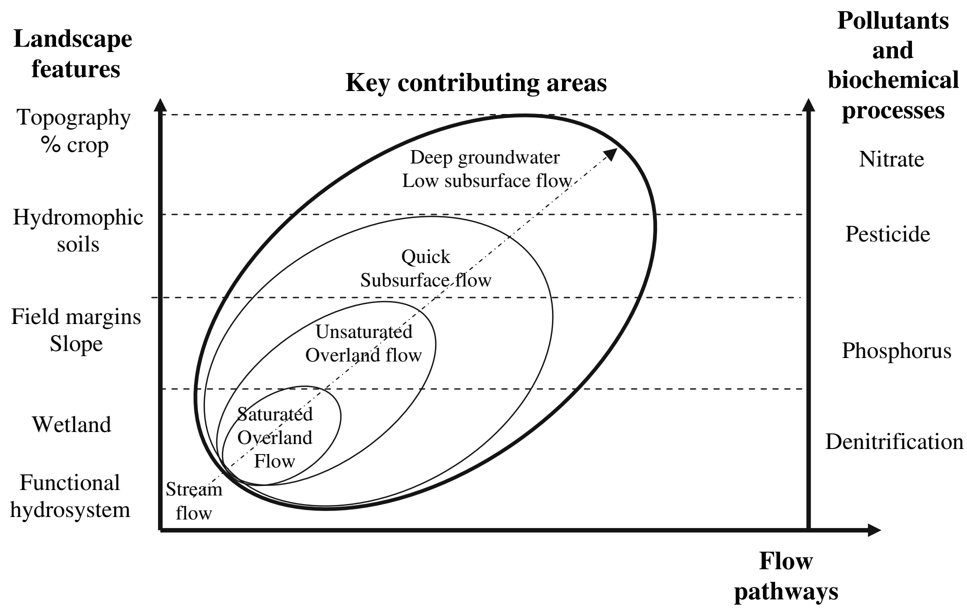

Fig. 2 Diagram showing link among flow pathways, pollutants and biochemical processes, and landscape features, for determining the key contributing areas per pollutant in the catchment

with other attempts (Burt and Pinay 2005), the interactions among hydrological zones, pollutant characteristics, and landscape features are completely explicit here (Fig. 2).

The third principle is the modular structure for the framework. Six modules compose it (Table 1). The first is the starting point for choosing which of the five modules should be applied. The first module allows us to identify the main issues of the territory, by collecting together all the available data and guiding the choice of modules and approaches to be adopted. This makes it possible to obtain a precisely defined agreement between all the end-user delegates and the stakeholders. The second module focuses on the environmental diagnosis of the landscape features and leads to the delineation of key contributing areas for each pollutant. Modules 3, 4, and 5 estimate pollutant fate scores at different scales, first by plot, then by sub-catchment, and, finally, over the entire catchment area. These three modules correspond to the three pollutants considered up to now: herbicides, nitrates, and phosphorus. Finally, the sixth module considers possible scenarios for changing the agricultural landscape and land uses, and evaluates their advantages and feasibility. We present only modules 2 and 4 here since they are the most innovative ones of this framework and can resume the approach.

Table 1 Modules of the Territ'eau framework

Module	Description	Area
1	Identification of main issues and constraints; collection of existing data	Community, catchment
2	Environmental diagnosis of landscape structures (streams, ditches, wetlands, field margins, etc.) and delineation of key contributing areas regarding different types of pollutants	
3–5	Estimation of pollutant fate scores per field and subcatchment. Three pollutants are considered: herbicide, nitrate, and phosphorus.	Field, farm, subcatchment, community, catchment
6	Individual and collective recommendations	

Module 2: Assessment of Landscape Features and Delineation of the Pollutant Contributing Areas in Relation to Stream Water Quality

The second module performs an analysis of the main features of the agricultural landscape, particularly those located along the stream. It consists in listing the landscape features, using descriptive criteria to characterize and quantify their functions in relation to stream water quality, and in delineating the contributing areas for each pollutant, in order to evaluate the pollutant fate scores on these areas, or simply optimize their extent.

- It comprises a classic delineation of the catchment, subcatchments, and homogeneous topographic units based on slope criteria and a rough inventory of the main land uses such as woodlands, croplands, and set-aside or urban lands, while pollution due to croplands can be averaged over the entire area. Then the following steps are developed:
- A delineation of the functional hydrographic network, including active flowing ditches
- A delineation of the riparian wetlands according to a gradient of knowledge and interest
- An inventory of the field margins that act on overland flow and quick subsurface flow

Each step is based on factors that can be expressed according to easily defined criteria. Some of these criteria have already been described and published, while others are new and specifically developed for this framework. They are detailed below.

Delineation of the functional hydrographic network is crucial to have a precise location of the river spring, an upslope delineation of the stream network, while the river spring can be diffuse, varying in space and time, and an exhaustive inventory comprising artificial ditches and natural rivulets. A "blue line" characterizes the hydrographic network on topographic maps from the French Mapping Agency (IGN) and, thus, defines the locations where regulations of stream and river bank have to be applied, but the beginning of this blue line is determined by unclear criteria that generally tend to underestimate the length of the functional stream network. This underestimation may concern up to 20% of the total length of the stream network (Aurousseau and Squividant 1995; Merot and others 2003). A method developed in the framework of the SAGEs (water management scheme) proposed criteria discriminating stream network from ditches. The method considers three criteria based on the present-day and past functioning of the stream: (i) current and visual criteria such as the presence of a talweg position, river bank, specific substrate made of sediment, and aquatic life (plant or animal); (ii) seasonal observations such as the presence of a precisely located spring or water flowing during rainless periods; and (iii) past and ancient observations—written (ancient map and cadastre) or oral (previous owners, old people, especially when rivulets are channelized) memory indicating the pristine state of the stream. The length of the IGN hydrographic network is enlarged by identifying the whole functional stream network and discriminating ditches from natural watercourses. This method is an expert knowledge and participatory method, allowing local people an appropriation of the stream network as a common resource. Beyond the inventory itself, it can facilitate the implementation of remediation, protection, and rehabilitation actions. Figure 3 shows an example of a map of the IGN hydrographic network. We can see that the functional hydrographic network is much more extensive than the IGN hydrographic network.

Delineation of riparian wetlands is important, as they are often neglected in national and regional wetland inventories, because they are small, scattered in the rural landscape, and considered ordinary nature. Because they are located in the bottomlands of the headwater watersheds, they strongly influence hydrology, water quality, and biodiversity over the whole watershed area. But various difficulties arise in their inventory. There is a wide range of definitions and methods to characterize and delineate wetlands, depending on the discipline, and therefore they are difficult to apply and to transmit to stakeholders. Then,

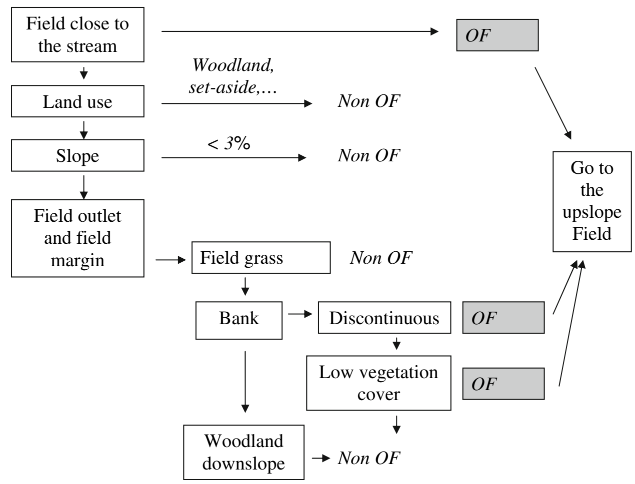

Fig. 3 Decision rules for delineating overland-flow (OF) contributing areas

despite a policy more and more favorable to wetland preservation, judicial and administrative rules are not as clear and constraining in the European and French contexts as the U.S. ones, especially for these small and narrow valley bottom wetlands. Finally, the conservation of wetlands as natural heritage and functional landscape structures is seldom taken into account by local stakeholders (farmers, municipality). The PEEWA method (potential, existing, efficient wetland approach) (Durand and others 2000; Merot and others 2006) defines potential wetlands by means of topographic criteria, while existing riparian wetlands are based on the observation of soil wetness. Efficient wetlands are based on the assessment of an environmental function, which can be a hydrological, biogeochemical, or ecological one function or a human one such as landscape or cultural heritage. A map of potential riparian wetlands is available for the entire region from a topographic index defined by Gascuel-Odoux and others (1998) and used by Aurousseau and Squividant (1995) and Merot and others (2003). The DEM was extracted from the elevation database for Brittany with a step of 20 m, produced by stereoplotting of panchromatic SPOT images to a resolution of 10 m. The drainage network was extracted from the 1:25,000 IGN map (National Geographic Institute, France). This map provides a common delineation of the potential wetlands for all stakeholders. It can be opened with Google Earth tools, which allow users to move to their catchment of interest and load a local map (http://agro-transfert-bretagne.univ-rennes1.fr/Territ_eau/Referentiel/Grilles_experts/-accueil.asp). Delineation of existing wetlands can be carried out according to the criteria developed by Durand and others (2000) from field observations of soil wetness. Figure 3 shows the differences between the potential and the effective riparian wetland areas. These differences may be due to agricultural drainage leading to artificial drying-up of the soils, limitations of the topographic indexes that fail to take account of local variations in topography, or variations of other factors such as soil and bedrock. The concept of potential wetlands can be considered a maximum envelope, a “negotiating” area, in which stakeholders have to decide on the wet territory to preserve or to recover, depending on the choice concerning the functions to foster (Merot and others 2006). Thus, the differences between the two types of wetlands can be considered an open domain for landscape management (Table 2). With a choice for extensive agriculture, these

Table 2 Expert matching tables assessing (a) extension of potential wetlands and (b) conservation status of wetlands per subcatchment

Potential wetland area		Potential buffer capacity
(a) Potential presence of wetlands		
0–10%		Low
10–20%		Moderate
>20%		High

Potential wetland area	Effective wetland area	Conservation status of wetlands
(b) Proportion of conserved wetlands		
0–10%	0–10%	Good
10–20%	0–10%	Moderate
	10–20%	Good
20–30%	0–10%	Low
	10–20%	Moderate
	20–30%	Good

areas can recover their environmental functions. From an operational perspective, this typology is a progressive one: we chose to classify the wetlands through a gradient of knowledge and interest.

Inventory of the field margins that act as a sink for overland flow consists in building a drainage network based on the identification of the inlets and outlets of each field and their related contributing areas, starting from the functional hydrographic network, going upslope, and stopping where a field margin acts as a barrier or an infiltrating area. Delineation of these areas and their links in terms of surface flow pathways provides us with a pattern of relationships between fields, going upslope from one plot to another, over the entire catchment, until we obtain a plot outlet tree, as described elsewhere (Tortrat 2005; Aurousseau and others 2008). The inventory of the landscape features that act in limiting this tree network, as developed by Baudry and others (2000) and Thenail and Codet (2003), includes the presence of woodlands or set-aside land along the functional hydrographic network, and of flat areas or field grass strips presenting continuous bank or vegetation cover in space and time (Fig. 4), which can modify efficiently the flow directions, the location of the plot outlets, and thus the size of overland flow areas. While the implementation of grassy strips and hedgerows is fostered in France as a part of cross compliance under the single payment scheme of the EU Common Agricultural Policy, end users can see the large decrease in the overland flow contributing area due to such implementations.

Finally, the approach described above allows us to determine (i) the functional stream network, i.e.,

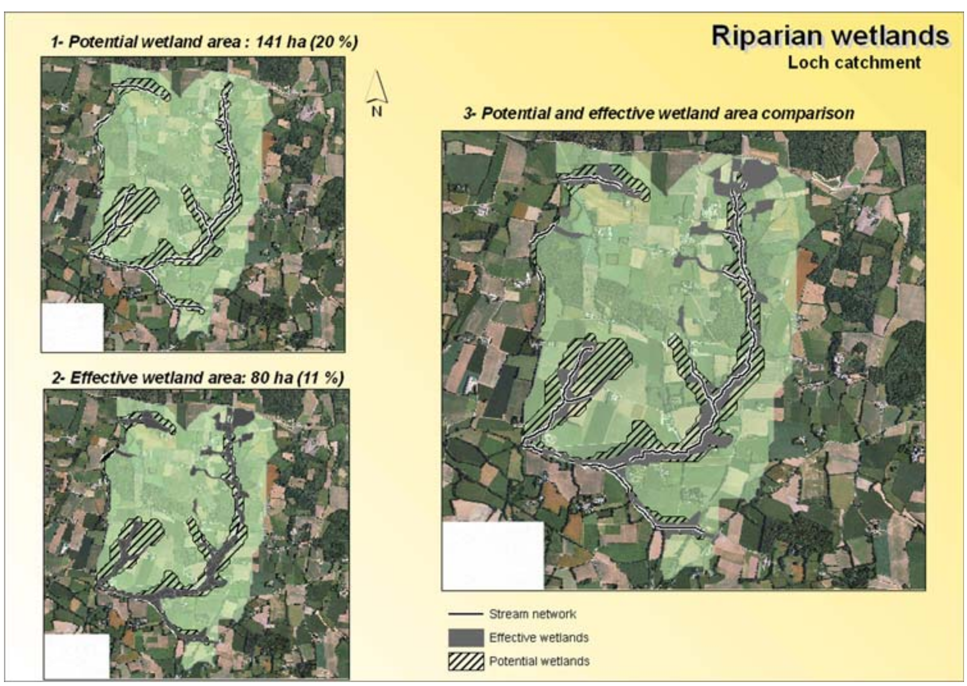

Fig. 4 Delineation of the functional hydrosystem, potential and effective wetlands on the Loch catchment (Morbihan, France)

modifications in the extent and location of the natural stream network due to agricultural management, (ii) the extent of the potential and effective wetlands, i.e., the proportion of conserved wetlands in each subcatchment and the range of potential denitrification, (iii) the key landscape features affecting the extent of overland flow areas, and (iv) the quick subsurface flow areas delineated by soil hydromorphic features. These areas correspond to potential areas because they are based on permanent criteria. They are usually less extensive and vary in space and time within these envelopes according to rainfall events and soil surface conditions. However, under unusual conditions, they may also be more extensive. However, we assumed that they correspond to the key contributing areas specifically for each pollutant, in order to evaluate and reduce the pollutant fate scores on these areas as described in module 3, 4, or 5 or simply to optimize their extent in module 2.

Module 4: Assessment of Nitrate Fate Scores in an Agricultural Catchment

The fourth module represents a semiquantitative estimate of the nitrate fate per field and subcatchment. The different steps are detailed below and in Table 3 and Fig. 5. First, the nitrate leaching is estimated per field. This estimate combines three factors: (1) a transfer coefficient due to the physical environment; (2) an estimate of nitrate leaching due to the crop system, under balanced fertilization and assuming a yearly mean value for each crop; and (3) an estimate of nitrate leaching in the event of surplus fertilization by the farmer. The latter two terms are added together to obtain an annual average of nitrate fate per hectare and year for each plot, then multiplied by the transfer coefficient per plot. This nitrate score is expressed as N units per plot, for the surveyed plots of each subcatchment (Table 4).

Table 3 Stages in the estimation of nitrate fate per field and subcatchment

Step	Description
1. Field map	Identification of field map on catchment
2. Surveyed area	If surveyed area represents more than 60% of catchment, the nitrate score per catchment can be calculated.
3. N excess in surveyed area	Mean N excess in surveyed area = Σ(N excess of each surveyed field $\times$ field area)/surveyed area
4. Subcatchment area	Subcatchment area is made up of a cultivated area and a noncultivated area (woodland, urbanland, roads, etc.). N excess is assumed to be 0 in noncultivated areas.
5. N excess per subcatchment	Mean N excess in subcatchment = mean N excess in surveyed area $\times$ (surveyed area/ subcatchment area)
6. N loss due to denitrification per subcatchment	Loss calculated from (a) Proportion of effective wetland (b) Characterization of denitrification function

The transfer coefficient is based on the annual water balance between precipitation and potential evapotranspiration (P-PET) during the mean period of recharge (October to March), as well as on soil properties. It is assumed that the nitrate remaining after the drainage period can be taken up by the following crops. If P-PET is higher than a threshold value (taken here as 300 mm), the transfer coefficient is 100%. If not, soil hydromorphy and depth are the two criteria used to determine this coefficient. P-PET is available from a regional map established from the mean of 30 years' observations. Soil depth and hydromorphy are determined from a 1:25,000 soil map if available or, otherwise, from local knowledge or a survey.

The two other terms require knowledge of the agricultural practices of the farmers located on the catchment basin. A survey is undertaken to identify the main crop successions by field or, rather, by groups of fields, because this saves time. This survey includes intercrops and locates crop successions on the field map. Some of the data are easily accessible because farmers have to register fertilization and pesticide applications since 2006 under the regional directives. A typology of the main crop successions with respect to nitrate leaching risk has been drawn up according to the regional references. Even if the fertilization is balanced in theory, different risks of N leaching are incurred by different crop successions, with or without temporary pastures. These risks depend on the importance and seasonality of the plant requirements, as well as the soil coverage, organic fertilizer application, and mineralization of plant residues. The nitrate fate per subcatchment is calculated only if the survey covers more than 60% of the whole surface area of the subcatchment. The method is rather classical but based here on local references (Machet and others 1997; Vertes and others 2002) (Table 4).

The nitrate fate scores per subcatchment are calculated considering both dilution due to nonagricultural areas and denitrification due to wetlands. The surface area used to compute the mean nitrate leaching per catchment is the whole area including agricultural fields and nonagricultural land (woods, set-aside land, roads, housing, etc.) assuming that leaching is nil under these nonagricultural areas.

Losses due to denitrification processes are a function of the existing wetlands. Although earlier studies do not deal with the efficiency of riparian wetlands in relation to denitrification, this aspect is developed in the Territ'eau framework from an analysis of the literature, as well as

Fig. 5 Scheme for estimating the nitrate fate per field and subcatchment

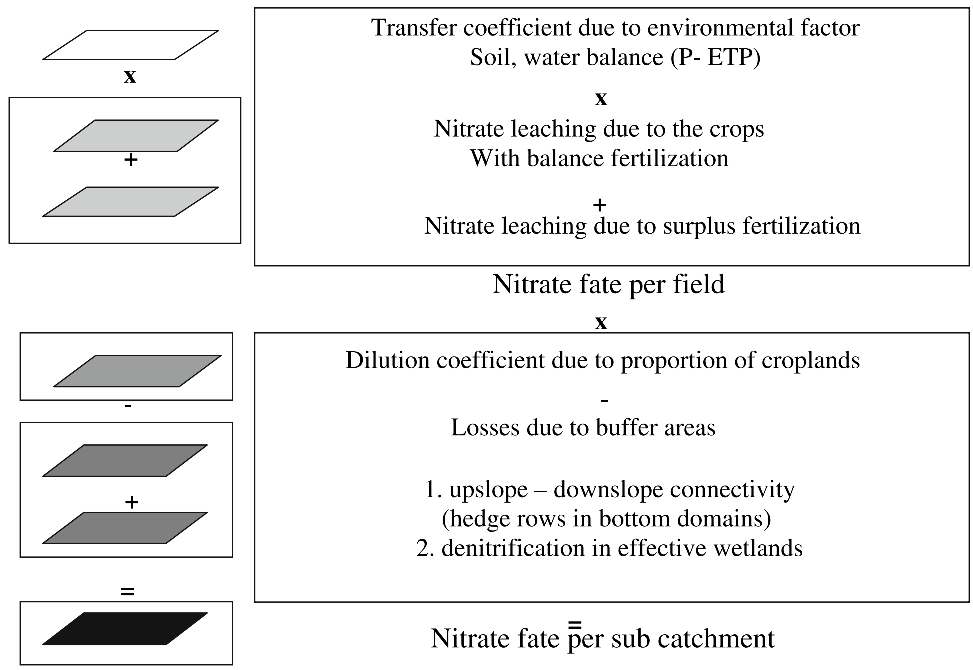

Table 4 Expert matching table to determine the nitrate fate per field according three criteria: crop succession type, transfer ratio, and overfertilization

Physical environment		Transfer ratio of N-excess equal to 100%			
Crop Succession regarding to a typology					
	Qualitative assessment	Very low	Low	Moderate	High
	Expressed in kg de N/ha/an	20	35	45	55
		*Combination of three factors (Physical environment * Crop Succession) + fertilization*			
Fertilization: N-leaching due to over-fertilization	Nil: 0	20	35	45	55
	Low: 15 (from 10 to 25 uN)	35	50	60	70
	Moderate: 35 (from 25 to 50 uN)	55	70	80	90
	High: 75 (from 50 to 100 uN)	95	110	120	130
	Very high: 125 (>100 uN)	145	160	170	180

Note: The shaded region indicates a qualitative gradient of acceptability (from light is right to dark is unacceptable)

experimental and modeling results (Bidois 1999; Durand and others 2000; Beaujouan and others 2001; Montreuil and Merot 2006). Three matching expert tables were produced by a local working group (Tables 5, 6, 7). The first table (Table 5) assesses the management of a given wetland by taking into account (i) the type of vegetation, considering its natural and cultural heritage value, i.e., the trophic status, use, and fertilization if it is a grassland, (ii) the continuity of the upslope field margins, and (iii) the bypass flow that deflects denitrification. This table determines if the management of the wetland can be optimized regarding the denitrification function and what it could be. The second table (Table 6) assesses qualitatively the denitrification per subcatchment due to wetlands, by way of two criteria: the proportion of effective wetlands per subcatchment and the proportion of well-managed wetlands by way of the previous table. This table indicates if the extension of the efficient wetlands is sufficient to induce any effect on nitrate fate and, if so, which management could optimize it and what recommendations could be formulated. The third table (Table 7) assesses the N fate score per subcatchment, based on N fate score due to field leaching and denitrification in the wetlands. The qualitative score related to the denitrification can up- or downgrade the N fate score from one to two classes, according to the conservation and the potential of denitrification of the wetlands. The results are illustrated in Fig. 6. We can see that the extension and management of the wetlands can

Table 5 Expert table for assessing the management of each effective wetland in relation to the denitrifying function

Wetland boundary	Water flow in wetland	Trophic status				
		Eutrophic vegetation +	Grassland		Crop -	Oligotrophic vegetation
			Sward, slightly grazed, or fertilized < 50 U +	Grazed and fertilized > 50 U, or grazed −		
Continuous hedge row +	No bypass flow +	+ + +	+ + +	+ + -	+ + -	Conserved wetland due to heritage value
	Bypass flow -	+ - +	+ - +	+ - -	+ - -	
Discontinuous or no hedge row -	No bypass flow +	- + +	- + +	- + -	- + -	
	Bypass flow -	- - +	- - +	- - -	- - -	

Note: +++ very good; +−+, −++, or −+− good; +−− or −+− moderate; −−+ or −−− bad

The shaded region indicates a qualitative gradient of acceptability (from light is right to dark is unacceptable)

Table 6 Expert table for assessing the denitrification per subcatchment and recommendations for improving wetland management

Proportion of effective wetlands per subcatchment	Proportion of well-managed effective wetlands per subcatchment	Denitrification per subcatchment	Recommended status
Below threshold (15%)	–	Bad (extension)	To be more extended
Above threshold (15%)	% moderate + good + very good <threshold (30%)	Bad (management)	To be managed
	% moderate + good + very good >threshold (30%)	Moderate	To be better managed
	% good or very good <threshold (50%)		
	% good or very good >threshold (50%)	Good	Good management

Table 7 Expert table for assessing the final N fate score per subcatchment, taking into account the conservation and management of the wetlands in the N fate score per field averaged per subcatchment

Conservation (Table 2b, column 3)	Denitrification (Table 6, column 3)	N fate score per subcatchment (Table 4, Results)			
		<25	25–50	50–100	>100
Good	Good	Very good	Very good	Good	Very bad
	Moderate	Very good	Very good	Good	Very bad
	Bad	Very good	Good	Rather bad	Very bad
Moderate	Good	Very good	Very good	Good	Very bad
	Moderate	Very good	Good	Rather bad	Very bad
	Bad	Good	Rather bad	Very bad	Very bad
Low	Good	Very good	Good	Very bad	Very bad
	Moderate	Very good	Rather bad	Very bad	Very bad
	Bad	Rather bad	Very bad	Very bad	Very bad

change the N pressure per subcatchment. The semiquantification of the denitrification in the wetlands highlights their buffer capacity but also delineates their limit in the case of a high N surplus on the hillslope. If the nitrate fate is very high, the conservation and management of the wetlands do not change the N fate, indicating that management of the riparian zone cannot solve the problem of the nitrogen excess, mainly due to the agricultural practices. On the contrary, if the nitrate fate is low or moderate, the conservation and management of the wetland can contribute to improving or deteriorating the N fate.

Finally, module 4 may be used to make land management recommendations: localization of critical plots and, on these plots, possible solutions, which can be related to

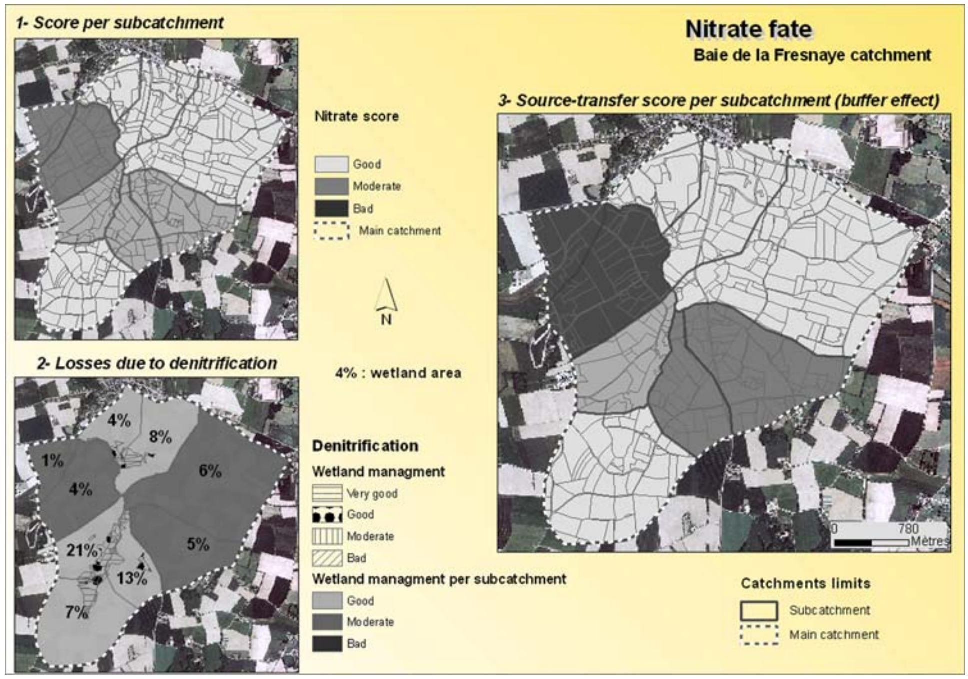

Fig. 6 Map of the estimated nitrate fate on the Baie de la Fresnaye catchment (Côtes d'Armor, France), considering, first, the nitrate score due to agricultural activities and, then, the nitrate fate considering the extension and management of the riparian wetlands

crop succession or to fertilization, and localization of riparian zones where the N fate can be improved by reducing fertilization, protecting the riparian zones from upslope by rebuilding hedges or closing bypasses. These recommendations can be combined, and a few alternatives reaching a target value can be proposed to the farmers.

The Overall Vision for this Framework and its Uses, and Plans for Future Improvements

Merits of the Territ'eau Framework for Agricultural Landscape Management

A Holistic Approach to the Protection of Water

(a) From a downscaling perspective, this framework includes productive as well as semi- or nonproductive areas, and involves assessing their function as source, sink, or buffer acting on the water quality. From an upscaling perspective, human and environmental data for the whole territory are used to establish the main human and environmental constraints and issues, explaining the specific features of the territory. The diagnostic is holistic but not exhaustive.

(b) This framework takes existing partial tools into account to avoid redundancy or interference with actions already in progress; for example, the PEEWA method was developed for riparian wetland inventories (Merot and others 2006) and is included in the Territ'eau framework, along with the herbicide risk index (Aurousseau and others 1998).

(c) On the contrary, it aims to propose a diagnosis on all the components of the water quality in the same framework, that is, nitrate, phosphorus, and pesticide at this moment and in the future. Generally tools for water management are focused on one type of landscape feature or pollutant.

Operational and Functional Knowledge of Pollutant Transfer in Agricultural Landscapes

(a) This framework provides stakeholders with a spatial view and diagnosis of the main hydrological and biogeochemical processes in the catchment. It also gives a corresponding delineation of the key areas affected by these processes, as well as the fate of the pollutants involved. In addition, the framework provides information and ways of assessing the effect of landscape features by modifying these key areas and their associated scores. The barrier or dilution effects of seminatural landscape features such as wetlands or woods are also highlighted. Therefore, this framework allows us to establish a functional partitioning of the catchment in terms of hydrological and biogeochemical functioning, placing emphasis on the effect of landscape features and natural areas. Finally, it facilitates a comprehensible and functional view of the catchment, using the concept of contributing areas to incorporate the effect of landscape features into this framework. This is a basic and important point, since landscape features are generally considered in relation to the biodiversity issue, while much confusion and even controversy remains regarding the water quality issue (Viaud and others 2004; Merot and others 2006).

(b) This comprehensible and functional view of the catchment is based on scientific results that are expressed in an understandable way so they can be appropriated by the end users. We propose a hierarchy as well as a quantitative or semiquantitative assessment of the effect of each landscape element, which should be as clear and precise as possible. Free access is provided via the Web site to all experimental, technical, and scientific references used for this assessment, specified for each type of landscape element, and expert rules are available to improve their management.

(c) A temporal view of the agricultural landscape also includes its present status, through the evolution of the landscape in both the past and the future. First, this approach reveals the baseline status compared to the present day, i.e., the difference between potential and existing wetlands, as well as between the hydrographic network and the functional hydrographic network. Second, the current status can be readily compared to the future status of the landscape, based on a scenario of landscape change, by using GIS for all the treatment steps and types of data. The inherited features of the landscape and their future evolution are thus taken into consideration.

(d) The current management of the landscape is also incorporated in this framework, while landscape features such as wetlands and field margins are treated differently according to their management. While conservation is generally the only aspect considered in other approaches, Territ'eau also considers landscape management as important, by encouraging the identification, assessment, and management of landscape features such as wetlands, similarly to Janssen and others (2005). In their paper, evaluation of the denitrification function is based on the management of the riparian wetlands inserted in the agricultural landscape. For example, the expert rules encourage low fertilization, continuous barriers (e.g., hedge, bank), and no shortcut from the upslope (e.g., ditches, artificial drainage). By way of quantification of the denitrification function, good management is promoted: it can decrease the nitrate fate of the subcatchment in some cases; on the contrary, it can increase it in other cases, or simply indicate that the wetland management is totally insufficient to solve a too-high N fate.

A Tool for Enhancing the Possibility of Governance

Agricultural landscapes have undergone tremendous changes since the 1950s: many riparian wetlands have been drained and hedgerows removed. The role of seminatural areas is still an open question since these areas fulfill multiple and increasingly recognized functions (Baudry 1997; Qiu 2003; Thenail and Baudry 2005). The limits are fuzzy between farmers' fields and seminatural areas: the field margins may be considered as belonging to productive, unproductive, or ecological areas (Baudry and others 2000; Baudry and Thenail 2004; Marshall and Moonen 2002), which might be protected or rebuilt in the future.

(a) This method improves the dialogue with farmers for the diagnosis and identification of solutions, because a large number of local and regional data, such as catchment area delineations, field maps, slope distribution, and potential wetlands, are collated before going into the field and visiting the farmers. Availability of the data improves the dialogue and the appropriation of the territory by the end users.

(b) Scenarios for landscape management offer a wide range of solutions, which may concern agricultural practices or even agricultural systems, on the one hand, as well as the location and extent of the seminatural areas, on the other hand. These are evaluated not only from a water quality perspective but also considering other environmental impacts such as biodiversity and amenities.

(c) A framework and all the tools are shared by scientists and stakeholders, to provide easily understandable and appropriable tools as a condition for setting up sustainable actions. The framework and tools have been developed and checked, step by step, during the 3 years of the project, including periodic meetings with different bodies such as environmental NGOs and consultants, farmers' delegates, and scientists. Although these tools are based on scientific knowledge, their design is cobuilt. Generally the scientists build a first draft based directly on scientific references, which are themselves based on simple and well-equipped situations, especially chosen for a scientific demonstration and described by the driving variables. These situations can be viewed as "archetype," while stakeholders consider a large diversity of situations, described by parameters and in the vocabulary they generally use. Therefore, it is necessary to reduce the gap and to transform the first scientific functioning schema into another one for a large audience of end users and situations. This transformation can only be achieved by a cobuilding process. Some stages of field data acquisition, such as delineation of streams or wetlands, may also include the participation of farmers or other land users who have a good knowledge of the area and can adapt the data to local conditions. These inventories can be delegated to consultants, but they can also be realized by different protagonists involved in the community (e.g., farmers, citizens, hunters), and it may be important to get a shared delineation and evaluation of the landscape structures in controversial situations.

(d) More generally, this approach opens up discussions on ways of finding appropriate solutions, which may include increasing natural spaces, improving landscape features and their management, and changing agricultural practices or systems. These discussions are open and negotiable. No stakes or legal constraints are considered in delimiting areas of interest such as woods or wetlands. Moreover, this allows stakeholders to be guided in agricultural landscape management by arguing the choices on a scientific basis, which is an important point in controversial areas. Generally, according to the final objective of improving water quality, changing agricultural systems or landscape features is viewed here as supplementing other environmental or productive functions as well as human and physical constraints.

A Tool for Obtaining Preliminary Data on and Expert Knowledge of the Landscape

(a) Preliminary and basic environmental data are made available for all the stakeholders. These data include the difference between precipitation and potential evapotranspiration during the 6 months of recharge, the area of potential wetlands derived from a topographic index, the organic matter content, and the erosion index. The data are available on maps that can be directly viewed and downloaded at the Territ'eau Web site or linked to free software (Google Earth). The availability of the data promotes the general interest in environmental data and a common basis for dialogue both within the catchment and between different catchments.

(b) Expert groups have developed various matching expert tables on the function of landscape features, and these have been applied to the characterization of wetlands. These tables fill a gap due to the lack of operational knowledge on environmental assessment of agricultural landscape features. These tables represent operational tools for landscape management, providing a semiquantitative approach to environmental functions that are difficult to assess but must be considered objectively for landscape features. They can be used to improve the conservation and management of such features; however, they do not offer a solution by acting as a buffer for any level of nitrate leaching.

(c) A GIS is used intensively before and during fieldwork, to implement as early as possible the easy access to available data such as the DEM, the topographic index defining the potential riparian wetlands based on a topographic analysis (Merot and others 2006). First, this allows a reduction in field data acquisition and leads to the development of interactive diagnosis with the end users to arrive at operational proposals (Basnyat and others 1999, 2000). Second, this allows us to register and monitor the evolution of the landscape as closely as possible, as proposed by some other authors (Clark 1998; Rao and others 2000).

General Applicability and Originality of the Territ'eau Framework

An Original Framework Compared with Other Framework Tools

The Territ'eau framework differs from other frameworks that provide source and transfer scores on agricultural catchments (Heathwaite and others 2000, 2003). These tools select a list of criteria and define classes for each pollutant. These criteria drive the data toward scores. Although the criteria are combined, the scores related to the sources are added, then multiplied by the scores related to the transfer. Finally, these tools distribute the scores over the catchment. The present approach differs in several aspects. First, the Territ'eau framework is not focused on one pollutant, but provides an overview of the hydrological processes crossed with the chemical characteristics of the pollutants on the catchment. It also takes into account the landscape features as well as the agricultural plots and the losses per plot and subcatchment, considering the buffer areas that can act on the field margins and the scale of the catchment. It may comprise a participatory inventory of some elements of the landscape such as wetlands of the stream network. The search for solutions is included in the framework. For these reasons, this method opens up a wide range of solutions, covering the issue of water quality from a holistic viewpoint. Second, the source and transfer scores are not exhaustively assessed on the catchment, except for nitrate, which is highly mobile and, thus, transits in soils and groundwater. Instead, the scores are estimated from downslope to upslope in the catchment, stopping as necessary at different positions within the active hydrochemical area. The connectivity of flow pathways from field to field is taken into consideration, and thus, the source and transfer scores are evaluated only on key hydrochemical surfaces. This method is therefore quicker and more precise, since it covers only a part of the catchment in a more detailed way.

This framework also differs from the modeling associated with the concept of critical source areas developed by Heathwaite and others (2005). Although their concept is very similar to that described in the Territ'eau approach, it is dedicated to small catchments and identification of detailed features such as tramlines, tracks, and fields draining to other fields within the catchment.

Some efforts have yet to be developed to validate this approach. However, this is not an easy task on real catchment, while many landscape elements, agricultural practices, and climatic characteristics are changing together and the response time can be long. The validation will probably come from modeling that will be able to consider more and more various situations in a realistic way.

General Application of Territ'eau to Other Physical Environments

The basic principle, which is the delineation of contributing areas, is general and applicable to any agroenvironmental context. Some authors are also beginning to use this concept in hydrology (Peschke and others 1999; Scherrer and Naef 2003; Leu and others 2004; Schmocker-Fackel, 2004). However, we can wonder wonder this framework offers a general advantage for agricultural landscape management relating to water quality or whether it depends too closely on the regional context from which it develops. However, we stress that this framework is particularly concerned with specific environmental and agricultural situations. In the first place, it is developed for humid and temperate climates, where the precipitation is higher than the potential evapotranspiration and the precipitation intensity is generally low, and thus, subsurface flow is dominant. In such catchments, the stream water comes from shallow groundwater. Riparian wetlands are located along the stream, while the water table is close to the soil surface and roughly linked to the topography. Under such conditions, numerous hydrological processes are involved, showing different combinations in space and time, crossing in various ways the chemical species pathways and reactivities. In these situations, stakeholders really need a comprehensive scheme/model of the hydrogeochemical functioning of the catchment based on a spatial analysis and delineation of the key areas. This would not be the case in deep groundwater systems or with total Hortonian overland flow systems.

Similarly, this is also particularly adapted to agricultural landscapes characterized by a dense field mosaic in which the field margins are numerous and varied. This is often the case in livestock farming systems, where fields are generally small and exhibit specific field margins such as hedgerows. In these situations, it is really important to incorporate the landscape features into such a scheme when the agricultural landscape is composed of a mosaic of fields, with different boundaries, interacting with water and pollutant flow pathways.

Otherwise, this framework is particularly useful in an agroenvironmental context where land use and management are controversial and where an objective assessment of the agricultural landscape features is needed to reflect the future of the territory concerned. While agricultural systems have to change progressively, optimizing the buffer capacity of the agricultural landscapes in relation to the water quality could contribute to improving the water quality as quickly as possible. But this function has to be objectively and collectively estimated so as not to mask the necessary changes of the agricultural systems while conserving the other environmental functions of the landscape. Many partial tools have already been implemented to deal with highly degraded water, but the present framework aims to combine these previous studies and include the different pollutants and agricultural landscape features.

Finally, all the typologies and expert matching tables produced in this framework must be reconsidered in view of the specificities of the agroenvironmental context in question. They have to be rebuilt or recalibrated according to each case and based on local references. For example, the typology of the crop systems and their associated tables are clearly context-specific. This applies also to evaluating the denitrifying function in wetlands.

Conclusion

Territ'eau is a new framework for diagnosing and improving agricultural landscape management in relation to water quality. This framework proposes a holistic approach for analyzing the territory as well as an environmental assessment of each aspect relating to water quality, including areas specialized in agricultural production, natural and seminatural areas, and linear landscape structures. This framework is based on a functional spatial analysis of the catchment, which defines the active hydrogeochemical areas controlling water quality in the streams. It improves the assessment of natural and seminatural areas according to their spatial extent and management in relation to the water quality issue. While this framework is new and its operationality remains to be validated and improved, it could be easily extended to incorporate other agricultural pollutants such as bacteria and organic dissolved carbon.

Acknowledgments This project was funded by the "Charte de développement pérenne de l'agriculture Bretonne," under a European programme (FEDER). We thank the staff of the regional farmer counsel organization (Chambre d'Agricultures de Bretagne), who contributed greatly to this framework, particularly Robert Blondel and Sylvie Tico, as well as the scientists and stakeholders involved in the discussions. M. S. N. Carpenter revised and edited the English.

References

Aurousseau P, Squividant H (1995) Rôle environnemental et identification cartographique des sols hydromorphes de bas-fonds. pp 75–85 in Ingéniéries, E.A.T. no spécial La rade de Brest

Aurousseau P, Gascuel-Odoux C, Squividant H (1998) Méthode d'évaluation d'un risque parcellaire pour la contamination des eaux superficielles par les pesticides. Etude et gestion des sols 5:143–156

Aurousseau P, Squividant H, Tortrat F, Gascuel-Odoux C, Cordier MO (2008) A plot drainage network as a conceptual tool for the spatialisation of surface flow pathways in agricultural watersheds. Computer & Geosciences (in press)

Basnyat P, Teeter L, Flynn KM, Lockaby BG (1999) Relationships between landscape characteristics and nonpoint source pollution inputs to coastal estuaries. Environmental Management 23:539–549

Basnyat P, Teeter LD, Lockaby BG, Flynn KM (2000) The use of remote sensing and GIS in watershed level analyses of non-point source pollution problems. Forest Ecology and Management 128:65–73

Baudry J (1997) Buffer zones and farming systems. In: Haycock N, Burt TP, Goulding KWT, Pinay G (eds) Buffer zones: their processes and potential in water protection. Quest Books, pp 275–282

Baudry J, Thenail C (2004) Interaction between farming systems, riparian zones, and landscape patterns: a case study in western France. Landscape and Urban Planning 67:121–129

Baudry J, Burel F, Thenail C, Le Cœur D (2000) A holistic landscape ecological study of the interactions between farming activities and ecological patterns in Brittany, France. Landscape and Urban Planning 50:119–128

Beaujouan V, Durand P, Ruiz L (2001) Modelling the effect of the spatial distribution of agricultural practices on nitrogen fluxes in rural watersheds. Ecological Modelling 137:93–105

Beaujouan V, Durand P, Ruiz L, Aurousseau P, Cotteret G (2002) A hydrological model dedicated to Topography-bases simulation of nitrogen transfer and transformation. Rationale and application to the geomorphology-denitrification relationship. Hydrological Processes 16:493–507

Bidois J (1999) Aménagement de zones humides ripariennes pour la reconquête de la qualité de l'eau: expérimentation et modélisation. Doctorat. Université de Rennes 1

Burt T (2001) Integrated management of sensitive catchment systems. Catena 42:275–290

Burt TP, Pinay G (2005) Linking hydrology and biogeochemistry in complex landscapes. Progress in Physical Geography 29:297–316

Cerdan O, Souchère V, Lecomte V, Couturier A, Le Bissonnais Y (2001) Incorporating soil surface crusting processes in an expert-based runoff model: sealing and transfer by runoff and erosion related to agricultural management. Catena 46:189–205

Clark MJ (1998) Putting water in its place: a perspective in GIS in hydrology and water management. Hydrological Processes 12:823–834

Cordier MO, Garcia F, Gascuel-Odoux C, Masson V, Salmon-Monviola J, Tortrat F, Trepos R (2005) A machine learning approach for evaluating the impact of land use and management practices on streamwater pollution by pesticides. In: Zerger A, Argent RM (eds) MODSIM 2005. Modelling and Simulation Society of Australia and New Zealand. International Congress on Modelling and Simulation, 12–15 December 2005, Melbourne, pp 2651–2557

de Roo APJ, Wesseling CG, Ritsema CJ (1996) LISEM: a single event physically-based hydrologic and soil erosion model for drainage basins: I. Theory, input and output. Hydrological Processes 10:1107–1117

Devillers J, Farret R, Girardin P, Rivière JL, Soulas G (2005) Indicateurs pour évaluer les risques liés à l'utilisation des pesticides. Lavoisier Tec & Doc, Paris

Dorioz JM, Wang D, Poulenard J, Trevisan D (2006) The effect of grass buffer strips on phosphorus dynamics—a critical review and synthesis as a basis for application in agricultural landscapes in France. Agriculture, Ecosystems & Environment 117:4–21

Dosskey MG (2002) Setting priorities for research on pollution reduction functions of agricultural buffers. Environmental Management 30:641–650

Durand P, Gascuel-Odoux C, Kao C, Merot P (2000) Une typologie hydrologique des petites zones humides ripariennes. Etude et gestion des sols 7:207–208

Gascuel-Odoux C, Merot P, Crave A, Gineste P, Gresillon JM, Zhang Z (1998) Les zones contributives de fond de vallée: localisation, structure et fonctionnement hydrodynamique. In: Cheverry C (ed) Le programme CORMORAN 'Caractérisation, observation et modélisation de la qualité des eaux en milieu agricole intensif. INRA, Paris, pp 129–142

Heathwaite L, Sharpley A, Gburek W (2000) A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. Journal of Environmental Quality 29:158–166

Heathwaite L, Sharpley A, Bechmann M (2003) The conceptual basis for a decision support framework to assess the risk of phosphorus loss at the field scale across Europe. Journal of Plant Nutrition and Soil Science 166:447–458

Heathwaite AL, Quinn PF, Hewett CJM (2005) Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. Journal of Hydrology 304:446–461

Janssen R, Goosen H, Verhoeven ML, Verhoeven JTA, Omtzigt AQA, Maltby E (2005) Decision support for integrated wetland management. Environmental Modelling and Software 20:215–229

Joannon A, Souchere V, Martin P, Papy F (2006) Reducing runoff by managing crop location at the catchment level, considering agronomic constraints at farm level. Land Degradation and Development 17:467–478

Leu CM, Singer H, Stamm Ch, Müller SR, Schawarzenbach RP (2004) Simultaneous assessment of sources, processes, and factors influencing herbicide losses to surface waters in small agricultural catchment. Environmental Science and Technology 38:3827–3834

Machet JM, Laurent F, Chapot JY, Dore T, Dulout A (1997) Maîtrise de l'azote dans les intercultures et les jachères. In: Lemaire G, Nicolardot B (eds) Maîtrise de l'azote dans les agrosystèmes. INRA-Editions, série Les Colloques de l'INRA. INRA, Paris, pp 271–288

Marshall EPJ, Moonen AC (2002) Fields margin in northern Europe:their function and interactions with agriculture. Agriculture, Ecosystems and Environment 89:5–21

Massa F, Gascuel-Odoux C, Merot P, Baudry J, Beduneau G, Blondel R, Durand P, Tico S, Troccaz O (2008) Territ'eau une méthode et des outils pour améliorer la gestion des paysages agricoles en vue de préserver la qualité de l'eau. Ingénieries (spécial issue: Azote, phosphore et pesticides):115–132

Merot P (1999) The influence of hedgerow systems on the hydrology of agricultural catchments in a temperate climate. Agronomie 19(8):655-669. doi:10.1051/agro:19990801

Merot P, Squividant H, Aurousseau P, Hefting M, Burt T, Maitre V, Kruk M, Butturini A, Thenail C, Viaud V (2003) Testing a climato-topographic index for predicting wetlands distribution along an European climate gradient. Ecological Modelling 163:51–71

Merot P, Hubert-Moy L, Gascuel-Odoux C, Clément B, Durand P, Baudry J, Thenail C (2006) A method for improving the management of controversial wetland. Environmental Management 37:258–270

Montreuil O, Merot P (2006) Nitrogen removal in valley bottom wetlands: assessment at a large catchment scale. Journal Environmental Quality 35(6):2113-2122. http://dx.doi.org/doi:10.2134/jeq2006.0091

Neitsch SL, Arnold JG, Kiniry JR, Williams JR, King KW (2002) Soil and Water Assessment Tool. Theoretical documentation. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, TX

Ouyang W, Hao FH, Wang XL (2008) Regional non point source organic pollution modeling and critical area identification for watershed best environmental management. Water, Air and Soil Pollution 187:251–261

Peschke G, Etzenberg C, Töpfer J, Zimmermann S, Miller G (1999) Runoff generation regionalization: analysis and a possible approach to a solution. IAHS Publication 254:147–156

Pilkey OH, Pilkey-Jarvis L (2007) Useless arithmetic. Why environmental scientists can't predict the future. Columbia University Press, New York

Qiu Z (2003) A VSA-based strategy for placing conservation buffers in agricultural watersheds. Environmental Management 32: 299–311

Rao MN, Waits DA, Neilsen ML (2000) A GIS-based modeling approach for implementation of sustainable farm management practices. Enviromental Modelling and Software 15:745–753

Reus J, Leendertse P, Bockstaller C, Fomsgaard I, Gutsche V, Lewis K, Nilsson C, Pussemier L, Trevisan M, van der Werf H, Alfarroba F, Blumel S, Isart J, McGrath D, Seppala T (2002) Comparison and evaluation of eight pesticide environmental risk indicators developed in Europe and recommendations for future use. Agriculture, Ecosystems and Environment 90:177–187

Scherrer S, Naef F (2003) A decision scheme to identify dominant flow processes at the plot-scale for the evaluation of contributing areas at the watershed scale. Hydrological Processes 17:391–401

Schmocker-Fackel P (2004) A method to delineate runoff processes in a watershed and its implications for runoff simulations. Ph.D. thesis. ETH, Zurich

Souchère V, King D, Daroussin J, Papy F, Capillon A (1998) Effects of tillage on runoff directions: consequences on runoff contributing area within agricultural watersheds. Journal of Hydrology 206:256–267

Thenail C, Baudry J (2005) Farm riparian land use and management: driving factors and tensions between technical and ecological functions. Environmental Management 36:640–653

Thenail C, Codet C (2003) Systèmes techniques de gestion des bordures de champs en exploitation agricole, et intégration des haies nouvelles. In: Lamarche H (ed) Bocagement, reconstitution et protection du bocage. Evaluation des politiques publiques de paysagement du territoire. INRA CNRS. Rapport de projet PEVS CNRS, Nanterre, pp 150–171

Tortrat F (2005) Modélisation orientée décision des processus de transfert par ruissellement et subsurface des herbicides dans les bassins versants agricoles. Thèse de l'Ecole Nationale Supérieure Agronomique de Rennes

U.S. Environmental Protection Agency (2008) Handbook for developing watershed plans to restore and protect our waters. Non Point Source Control Branch, Washington, DC

van Lanen HA, Demuth S (eds) (2002) FRIEND 2002. Regional hydrology: bridging the gap between research and practices. IAHS Publication 274. IAHS, Paris

Vertes F, Journet M, Alard V, Etesse A (2002) Le pâturage et les pertes d'azote. In: Alard V, Béranger C, Journet M (eds) A la recherche d'une agriculture durable: étude de systèmes herbagers économes en Bretagne. INRA Editions, collection "Espaces ruraux." INRA, Paris, pp 115–144

Viaud V, Merot P, Baudry J (2004) Hydrochemical buffer assessment in agricultural landscape: from local to watershed scale. Environmental Management 34:559–573

Viaud V, Durand P, Merot P, Sauboua E, Saadi Z (2005) Modeling the impact of the spatial structure of a hedge network on the hydrology of a small catchment in a temperate climate. Agricultural Management 74:135–163

Wang X, Yang W, Melesse AM (2008) Using hydrologic equivalent wetland concept within swat to estimate streamflow in watersheds with numerous wetlands. Transactions of the ASABE 51:55–72