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Modelling scenarios of agriculture changes on freshwater uses and water quality at a large watershed scale – the case of the Charente watershed (France)

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Abstract: The Charente River Basin (10 000 km2) is linked to the Pertuis Charentais Sea by a large tidal influence. The agriculture impacts strongly the quantity and the quality of freshwaters and influences the salinity and the quality of coastal waters needed by the oyster culture. In the context of 2 projects dealing with ICZM (EU Spicosa project, Respireau), we focused on the environmental assessment of spatialised scenarios of changes in agriculture.

Different methods of clustering and data analysis were used to define a relevant typology of spatial units on the area. Combined with an analysis of agricultural practices based on surveys (irrigation, fertilizers and pesticides), the agricultural activities can be described in a simplified way, to be linked with hydrological models regarding the water quantity and quality. Scenarios are built using surveys, expertise and discussion with stakeholders. Measures for agriculture changes are either considered in the agro-environmental programs or defined by stakeholders. Their effectiveness on the reduction of nutrients and pesticides fluxes is assessed when applied on the whole area or within sub-basins, depending on the farming system and vulnerability. Assessment was carried out using the spatially distributed model SWAT. The effectiveness of each scenario is considered in terms of relative reduction of water uptake for irrigation, nitrates, pesticides, suspended matter compared to the current situation.

***Keywords**:* AGRICULTURE, SCENARIOS, WATER RESOURCES, SWAT MODEL, INDICATORS, PESTICIDES.

1. Introduction

Agricultural policies have recently experienced major reformulations and have become more spatialised. Defining policy priorities requires appropriate tools (indicators, models) with relevant results about ecological and social features of agricultural practices (CEC, 2001). Concerning water resources, a major policy issue is currently the implementation of WFD (Water Framework Directive) in European countries. It stresses that an assessment is required to implement efficient measurement programs to preserve or restore the good ecological status of water bodies (to be reached in 2015).

Compliance with this WFD implies a reduction in the impact of agricultural pressure on the environment and the implementation of measures designed to reduce pollution of surface and ground waters from agriculture. The river basin has been designated as an appropriate level for an integrated water management. In this approach, both point and non-point sources (NPS) of pollution are subject to control. Pollution from NPS typically includes nutrients and pesticides applied to the arable land surface. The European Parliament recently approved a new EU pesticides legislation (to be implemented in 2011). Member States must adopt National Action Plans for reducing "risks and impacts" of pesticide use

on human health and the environment, including timetables and targets for use reduction. They must take measures to protect the aquatic environment from the impact of pesticides. These are to include "buffer zones" around water bodies and "safeguard zones" for groundwater used for drinkable water. In France, the program "Ecophyto 2018" aims to a specific reduction target of 50% for pesticides. The funding available for these mitigation measures must be used in the most effective way. As the characteristics of agricultural production may differ across a catchment, policy instruments can lead to extremely different results in terms of environmental effectiveness and consequently in terms of implementation costs. The aim of this paper is to propose a methodology for characterizing the agricultural activities and their possible evolution (scenarios) at the scale of a large river basin, in a distributed way and for evaluating the environmental impact of the chosen scenarios using modelling and indicators. The goal is to provide operational results for the science-policy discussions, in the context of stakeholders or local managers groups.
The work from which results are presented here was conducted in the Charente river basin (10 000 km2) and Pertuis Charentais Sea, in the context of two projects dealing with ICZM. The European project SPICOSA (Science and Policy Integration for Coastal System Assessment) proposed a system approach framework and integrated assessment platforms, in order to consider the ecological, social and economical dimensions of coastal systems management (Prou and al, 2009). The Respireau project (French National Program Liteau) is centred on the discussion process between scientists and stakeholders and deals with the water quality issue on the same area.

2. Material and methods

2.1 The Charente river basin

Agriculture activity covers about 60% of this area and about 11% of the cultivated area is irrigated. The annual water supply to human activities is 4 millions m3, with 34% dedicated to drinking water and 57% to irrigation which are therefore the two main human activities of concern in the freshwater issue. This river basin shows a risk of failing the objectives of the WFD towards the good ecological status (52% of the water bodies), due to agriculture diffuse pollution (nitrates, suspended matter and pesticides) and water shortage recurrent events. In addition, these failures of the freshwater management system have impacts on the marine waters (salinity) and the coastal ecosystems.

2.2 Spatial analysis

Different zoning methods could reveal these new entities by making it possible to identify units of systems with the same functioning at a selected level. First we chose the WFD elementary spatial units to analyse all variables at this scale. The WFD spatial unit (water bodies) is the elementary partition of aquatic environments selected for the water status assessment (140 hydrological units). A special focus has been done on some representative sub-basins (Né for both quality and quantity issues, Boutonne for intensive irrigation, Arnoult for pesticides). We also took in account reference spatial units (RSU) which are homogeneous parts of the river basin for selected variables. Some variables concerning structural sensitivity (slope, soil and drainage) are needed to assess the potential risk of agricultural pesticide or nutrients transfers towards surface waters. On the other hand, data about soil occupation and human practices, also needed, are available at the administrative entities scale. The territorial limits of environmental zoning do not fit with the French administrative limits, so that we have to use specific methods to take in account the different levels of organization (Daalgard and al, 2003). Aggregation and breaking up tools allowed recovering the agricultural data at RSU scale. (Vernier and al., 2010).

2.3 Clustering and typologies

When all the values for the chosen variables are calculated at the scale of spatial entities, data analysis tools can be used for clustering and defining relevant groups of spatial units for both geographic and thematic fields. Classical clustering methods (Parti-decla method) were applied to build a typology of RSUs. A new method using geographic constraints was tested: DIVCLUS-T is a descendant hierarchical clustering algorithm based on a monothetic bipartitional approach allowing the dendrogram of the hierarchy to be read as a decision tree. It was applied to RSUs described by agricultural and environmental variables, in order to take their geographical contiguity into account in the monothetic clustering process (Chavent and al, 2008). This typology was built to describe the Charente watershed and the agricultural activities in a simple way. So we can describe the agricultural activities (SAU, irrigated SAU, technical parameters and uptake of water in a spatialised way or in an aggregated way. We also built a typology of farming systems using statistical data from Agricultural Census and Common Agricultural Policy data. This typology can be used to generalize the data about agricultural practices (irrigation, fertilizers and pesticides) at the large river basin scale.

2.4 Scenarios

Besides the consultation of a participant group regarding the scenarios of evolution of the system (local managers) (Prou and al, 2009), we performed specific surveys among local authorities and professionals (experts, advisers, farmers) about the evolution of Agriculture in the next ten years. 2020 is relevant for two main purposes in terms of public policies: WFD specific programs (2015) and agro-environmental measures (MAET, Ecophyto 2018). These surveys allow proposing to stakeholders, different options for the evolution of agriculture, regarding the potential impact on the water resources. The scenarios are built following a participative approach. They are intended to function as combinations of future trends for climate, soil occupation (increase, decrease or change) and management options.
The current situation of agriculture on the area is defined as the baseline scenario "scenario 0". The parameters for this scenario 0 are defined by regional references, the previous work and the surveys made on the area. Each other scenario to be simulated is an occurrence of this first one. For each scenario, a calculation of all variables used has to be done for each sub-basin. Therefore, one global scenario on the Charente river basin comes in different local scenarios for each spatial unit (RSU) used in the models.

2.5 Effectiveness assessment – agro-hydrological modelling

The effectiveness of scenarios to reduce environmental impacts from agriculture is assessed using the semi-distributed river basin Soil and Water Assessment Tool (SWAT) model. (Arnold and al., 2005, Neitsch and al., 2001). The SWAT model was chosen for its ability to simulate nutrients and pesticide concentrations at the watershed scale, its worldwide use and its potential to simulate agricultural management practices. The model integrates all relevant ecological, hydrological and in-stream processes at the sub basin scale. The RSus of the SWAT model are called Hydrological Response Units (HRUs) in which the vertical, lateral and sub-lateral flows of water and nutrients are calculated. Some specific calculations (Lescot and al., 2009) are made to define relevant spatial land use entities in order to build the HRUs while intersecting data about soils and climate (4648 HRUs on the studied area). The management practices are defined at the HRU level by specific management operations (beginning and end of growing season, timing of cultural operations, timing and amount of fertilizers and pesticides spraying, irrigation management). Nutrients and pesticides fluxes from HRUs are routed to the 140 subbasin outlets. Several changes in the source code of the SWAT model were introduced for equations determining the FILTER function. In urban zones, we took herbicide spraying into account. Attention was paid to implementing an estimator for point losses such as those related to the cleaning of dressing/spraying equipment and to improve the representation of physical processes in filter strips. (Veerle and al, 2008). Once the model is modified and calibrated, it can be used to simulate the chosen scenarios and evaluate their effectiveness.
Before calibration and validation of SWAT, manual sensitivity analysis was carried out using a method similar to the one proposed by Ullrich and al (2009). The most sensitive parameters were CN2, USLE-P and Filter and these parameters were calibrated by comparison with measurement data. For point source pollution, we followed recommendations given by Gevaert (Veerle and al, 2008).

2.6 General approach (assessment)

The links between the different methods used are summarized in figure1. The definition of the typologies of farming systems and practices per RSU, the definition of scenarios and the discussion about their effectiveness and environmental impacts (in progress) include a participative process. Some scenarios can be simulated using the SWAT model (daily time scale for a 22 year period) and some others not. The results are about the scenarios which have been currently simulated. New iterations taking in account stakeholders' remarks are to be done.

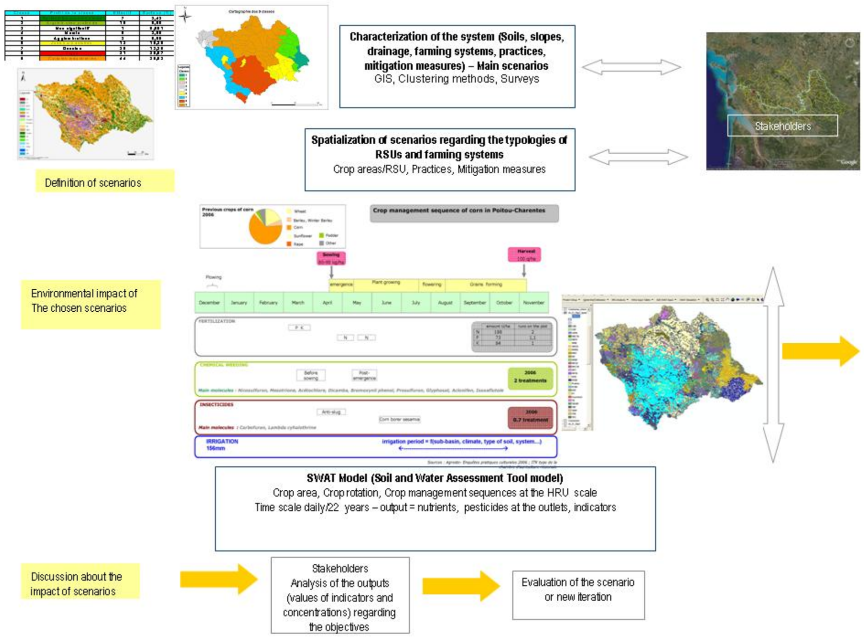

Figure 1: General approach

3. Preliminary results

3.1 Characterization of the agriculture in the river basin

Eight classes of RSUs (140 hydrological units) and five main farming systems were defined on the area using the clustering methods detailed previously. For each RSU, crop areas and crops areas are defined, as well as the type of watering uptake (figure 2). Using these two typologies, a crop management sequence including fertilization, pesticides and irrigation practices (see the example of maize in figure 1) can be allocated for each main crop and each sub-basin of the area. These values are used as an entry to the management files of the models for the scenario 0. Regarding the crop rotations, surveys allowed defining the main crop rotations for irrigated and non-irrigated crop area, depending on the type of soil and of the farming systems (table 1).

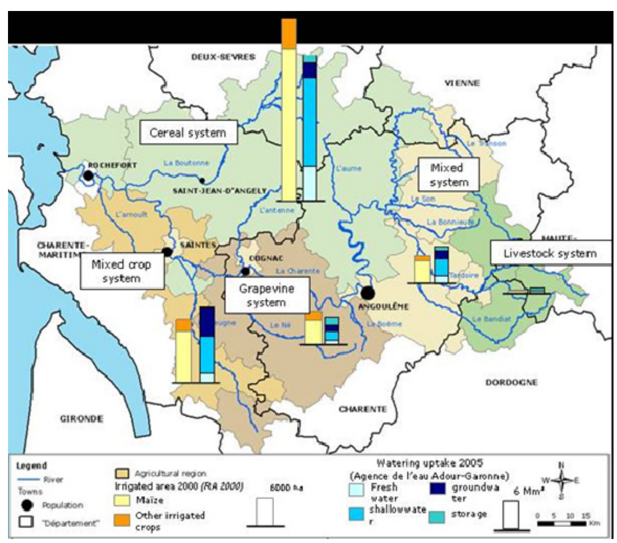

Figure 2: Types of farming systems and water uptake on the area

Table 1: crop rotations depending on soil and farming system (two types of soils among 7 defined on the area)

Type of soil	Crop rotation : Non irrigated	Irrigated
Doucins (silty soils)	maize / wheat / wheat or barley rapeseed-wheat-sunflower-wheat	Maize
Marshland soils, valleys, terraces	Maize rapeseed-wheat-sunflower-wheat	Maize Maize-wheat-barley

Using these data, we calculated at the RSU scale some agro-environmental indicators combining pressure from agriculture and sensitivity (soils, slopes, drainage). These indicators are useful for setting the different parameters of scenarios.

3.2 Scenarios

The main options defined with the stakeholders about the evolution of Agriculture in the next ten year are presented in table 2. The reference values for crop rotations and crop management sequences defined for the baseline scenario (scenario 0) are adapted and spatialized at the RSU scale for each simulated scenario. The values of the areas of irrigated and non irrigated crops are recalculated in a spatialised way for each sub-basin, and also the percentage of water uptakes from different sources (river, reservoirs and groundwater).

Table 2: main options from the stakeholders (if simulated in bold)

Soil occupation by agriculture	increase for non irrigated crop area	**Decrease for irrigated crop area**	Stability of increase for total arable land
Crop rotation	**diversification**	more spring or winter crops (less single crop farming)	**More "catch crops" implemented**
Types of crops	More industrial crops (hemp)	Increase for wheat, sunflower and leguminous plants	**Decrease for irrigated maize** and rapeseed
Water uptake	More dams	**Less authorised uptake**	Specific varieties of crops (less water demand)
Nutrients	More organic farming systems and grasslands		
Pesticides	**- 10 à -20% of pesticides applied**	- 30 % pesticides applied	More organic farming systems and grasslands **Riparian buffers**

3.2.1 Irrigation scenarios

Considering the options chosen by the stakeholders, our expertise on the area and the constraints from the simulation model, the simulated scenarios are (currently):
- IR0: scenario without irrigation on the area. It comes from the baseline scenario (business as usual) but without any irrigation. This "virtual" scenario is used as a calibrating one,
- IR1: scenario which fits with less authorized uptakes; irrigation is forbidden when the river flow reaches a threshold of 12 $m3\ s^{-1}$,
- IR2: scenario without any threshold for the uptake in the river; it is also a calibrating scenario, all the water available in the river could be used for irrigation uptakes.

The SWAT model calculates the daily volume needed for the irrigation of the irrigated crop area on the sub-basin and then the type of water uptake (from the river, from the water table or from reservoirs) is defined in some parameters with the values coming from the previous steps (see paragraph 3.1).

3.2.2 Scenarios for pesticides assessment

Some mitigation measures were tested:

- RBS: setting riparian buffers all along river courses, except when soil occupation is grasslands or meadows ; the parameters chosen are 5, 10 or 20 meters wide (RBS5, RBS10 and RBS 20),
- CC: catch crop implemented between winter crops and spring crops,
- RP: decrease in the quantity of pesticides applied (RP10, decrease of 10%, RP20 decrease of 20%); stakeholders thought these values are the more realistic,
- LR-R: diversification in crop rotations with increasing the areas of winter rape,
- LR-P: diversification in crop rotations with increasing the areas of pea (protein plants).

Most of these scenarios were evocated by the stakeholders. They are used in the current mitigation measures proposed on the area. Several others scenarios are going to be simulated and proposed for discussions and feedback to stakeholders.

3.3 Results of simulations

The results presented in the tables 3,4 and 5 consist in annual means for the 12 last years of the 22- year- period simulation based on a daily calculation of all variables. Some indicators can be calculated for each scenario (crop yields). These indicators can be used to calculate a deficit of crop production due to some strategies (economic impact assessment).

Table 3: Impact of irrigation strategies on the river flow (for 3 chosen scenarios)

	Number of days (June to October) with a daily discharge threshold of						
	1 m3/s	**6 m3/s**	**8 m3/s**	**10 m3/s**	**12 m3/s**	**14 m3/s**	**16 m3/s**
S0	0	0	0	0	3	4	6
IR1	0	2	3	4	10	11	12
IR2	13	18	21	23	26	28	30

Table 4: Impact of irrigation strategies on the nitrates, pesticides and suspended matter (for 3 chosen scenarios)

	ET (mm)	**Irrigation rate (mm)**	**SM ($T\ ha^{-1}$)**	**Erosion ($kg\ ha^{-1}\ an^{-1}$)**	**N03-N ($T\ an^{-1}$) ***	**Pesticides ($\mu\ l^{-1}$)**	**Crops yields $TMS\ ha^{-1}$**
S0	365	0	23600	530	35100	1.06	6.9
IR1	371	140	25000	580	33400	1.10	9.0
IR2	410	160	30000	290	25200	1.15	10.1

ET evapotranspiration ; SM suspended matter in the river ; Erosion at the HRU scale ; Pesticides sum of the molecules ; crop yields in tons of dry matter per hectare

The comparison of hydrological effectiveness is carried out and considered in terms of relative reductions in a particular pollutant for scenarios regarding nutrients and pesticides.

$$\text{Effectiveness}_{(\%)} = 1 - \frac{[C_s]_{\mu g l^{-1}}}{[C_o]_{\mu g l^{-1}}}$$

with $[C_s]_{\mu g l^{-1}}$ Average concentration over the ten last years of hydrological simulation $[C_o]_{\mu g l^{-1}}$

Baseline concentration

Effectiveness is computed at the outlet of each HRU, at the outlet of each sub basin and at the Charente river basin outlet.

Table 5: effectiveness of scenarios to reduce the river concentrations at the outlet

Effectiveness (%)	**RBS 5**	**RBS10**	**RBS20**	**CC**	**RP10**	**RP20**	**LR-R**	**LR-P**
pesticides reduction	25	41	59	16	23	30	-12	9
suspended matter	13	21	31	- 1	4	4	5	1

reduction								
nitrate reduction	0	3	5	30	0	0	- 8	5

The figures 3a and 3b show an example of graphic output of the modelling of the baseline scenario (scenario 0) and of the RBS5 scenario. This type of output is produce for all the simulated scenarios in order to be discussed with stakeholders.

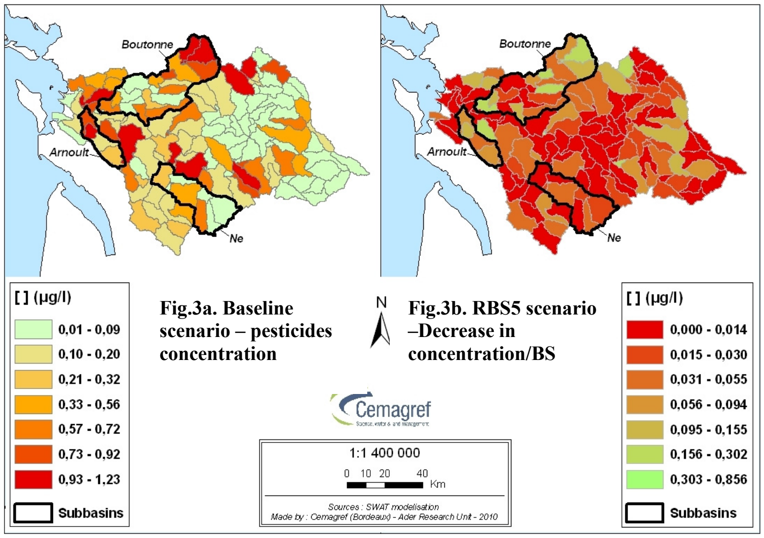

Figure 3a and 3b: spatial restitution of the simulation results for two scenarios, the baseline scenario and the RBS5 scenario (riparian buffers)

The results from table 3 show that irrigation impacts strongly the discharge of the Charente River even if the irrigated area is only 10% of the total cultivated area. Without policy constraints on water uptake for irrigation, crop production is higher but the river flow during the dry period decreases dramatically and doesn't allow a good functioning of the ecosystem; problems could occur for the uptake of drinkable water. These values are given for the Charente water course and more difficulties appear in upstream water bodies. The results presented in table 4 assert that irrigation influences the other factors of water quality. The IR2 scenario without constraints on irrigation water uptakes increases the concentrations in pesticides and suspended matter; the same scenario decreases the nitrate concentrations due to a better use of fertilization on the plots. The IR1 scenario which fits with less authorized water uptakes for irrigation is efficient mainly regarding the river flow (biodiversity).

As described in previous studies (Lescot and al, 2009), it is shown in table 5 that the riparian buffers (RBS scenarios) are effective for reducing the pesticides concentrations in the river course. These measures are applied on a small cultivated area and consequently the costs to implement them are not very high. Despite of this efficiency, these scenarios are not effective enough to decrease the concentration under a value of 0,5 µg/l which is considered as a standard (for all molecules) in current policies. These scenarios should be combined to other mitigations measures regarding the amount of pesticides applied on the plots. The RP scenarios (RP10, RP20) have a good effectiveness (20 to 30%) for reducing the pesticides concentrations. In these scenarios, a part of the herbicide spraying is replaced by mechanical weeding (zero herbicide) and not by other molecules. Another explanation is that herbicides are mainly found in the rivers, more than fungicides and insecticides. So the main cultivated area (cereals, maize and rapeseed) is concerned by this strategy. The catch crop scenario (CC) is also interesting because the action is effective regarding both nitrates and pesticides whereas RBS scenarios are less effective for reducing nitrates (particularly in well-drained areas).

The response of the sub basins to the pesticide pressure from agriculture is very different depending on their location in the river basin and on the natural and human conditions (figure 3a). Consequently, the effectiveness of each scenario comes in different ranges depending on the HRUs and sub basins (figure 3b).

1.5 Conclusions and Recommendations

The methodology used, based on several methods of diagnosis, spatial analysis, clustering and distributed modelling was tested at the scale of a large river basin, which is a relevant scale for integrated water management, seems effective for evaluating "ex-ante" the potential impacts of the possible evolution of Agriculture on the area. The typologies of RSUs and agricultural practices, then the results given by the simulations provide relevant output indicators for the science-policy discussions and more objectivity in the debate between stakeholders. The spatial resolution used for the restitution (maps) provides additional information for the management of the local areas or the implementation of mitigation measures on the area. The long-term time scale used for the simulations allows freeing from the short term variability like annual climate variations, annual variation of agricultural practices and therefore a better interpretation of water quality monitoring (mainly for pesticides). Another interest of this methodology is to provide a multicriteria evaluation (nitrates, pesticides, suspended matter and discharge) of each chosen scenario. The participatory process (discussion with stakeholders) can be taken in account with possible iterations for each scenario, to test several assumptions.
The preliminary results show some scenarios could be effective for reducing the pesticides concentrations in the rivers but it will be necessary to implement the mitigation measures in a relevant way depending on the sub basin (farming systems, natural conditions) and on a large cultivated area. The most effective scenarios (RBS scenarios) should be implemented in the largest range of farms but the concerned cultivated area is quite small (5 to 10 meters along the river). A perspective of the method could be a coupling with an economical model to assess the cost of implementation of the most effective scenarios, depending on the farming systems and the "on contract" cultivated area (CE cost effectiveness methods).

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