Cost-effectiveness analysis for controlling water pollution by pesticides using SWAT and bio-economical modeling

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Plan

- Context
- Methodology + Case study
- Effectiveness assessment (SWAT)
- Costs assessment (Bioeconomic model)
- Main results
- Conclusion

Introduction

❖Protection of surface waters quality requiring measures

Regulations and directives (Nitrate Directive (91/676/EEC), the Water Framework Directive (2000/60/EC), Pesticide Directive (2009/128/EC))

❖ Compliance with the Water Framework Directive (WFD) implying a reduction in the impact of agricultural pressures

❖ Public participation in water management required in international conventions that should be meaningful when issues are complex and uncertainties high (United Nations, 2000; Aarhus Convention, 1998; World Water Commission, 2000; WFD, 2000)

→ Agri-environmental measures defined at National or Regional level can lead to extremely different results in terms of implementation costs and environmental effectiveness

❖Cost-effectiveness analysis (CEA)

❖Government and Water agencies have to manage limited budgets allocated to the implementation of measures

❖CEA to be used to select combinations of measures at the water body and river basin level allowing for the attainment of the desired ecological objectives at the lowest costs for society (WATECO)*

→ Use of modeling tools for analyzing the different impacts and costs of environmental policy measures

- Could help define least costs programmes

- Long periods of time

Cost-Effectiveness Analysis (CEA) framework

Scenarios
measure or combination of measures

Stakeholders

Economic component
Mixed integer Linear Programming model
(commune level)

Environnemental component
Soil and **W**ater **A**ssessment **T**ool model
(management practices defined at the commune level)

Cost assessment of implementing measures
(Commune then sub river basin level)

Effectiveness assessment of mitigation measures on reduction of pesticides concentration at the outlets
Region water basin, Catchment, Sub-basins levels

Spatially distributed Cost-Effectiveness Analysis
of scenarios at the sub basins and catchment level

Targeting action programmes

Effectiveness of mitigation measures with SWAT

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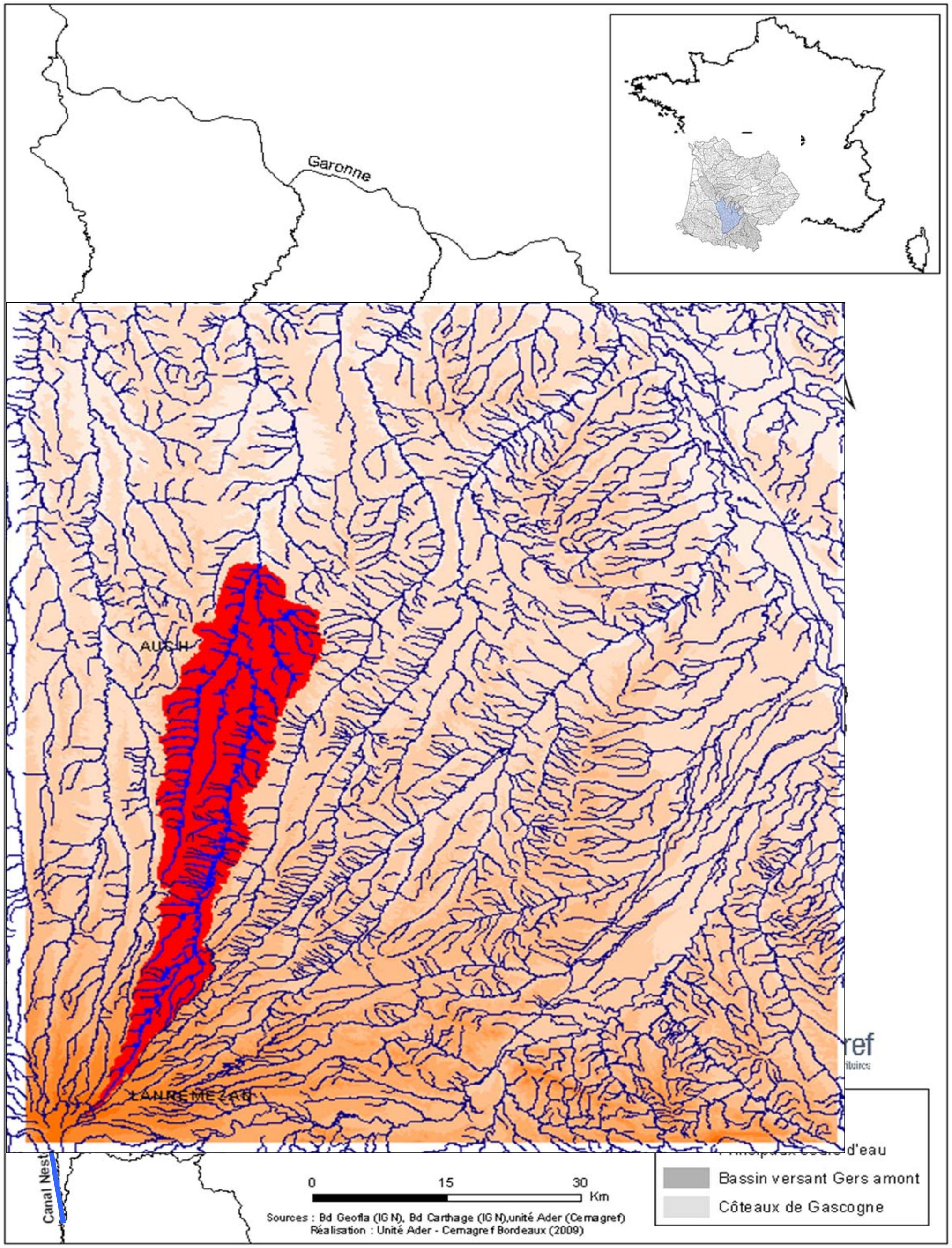


Case study

- The Gers river basin (sub basin of the Garonne river basin) in the South-western part of France

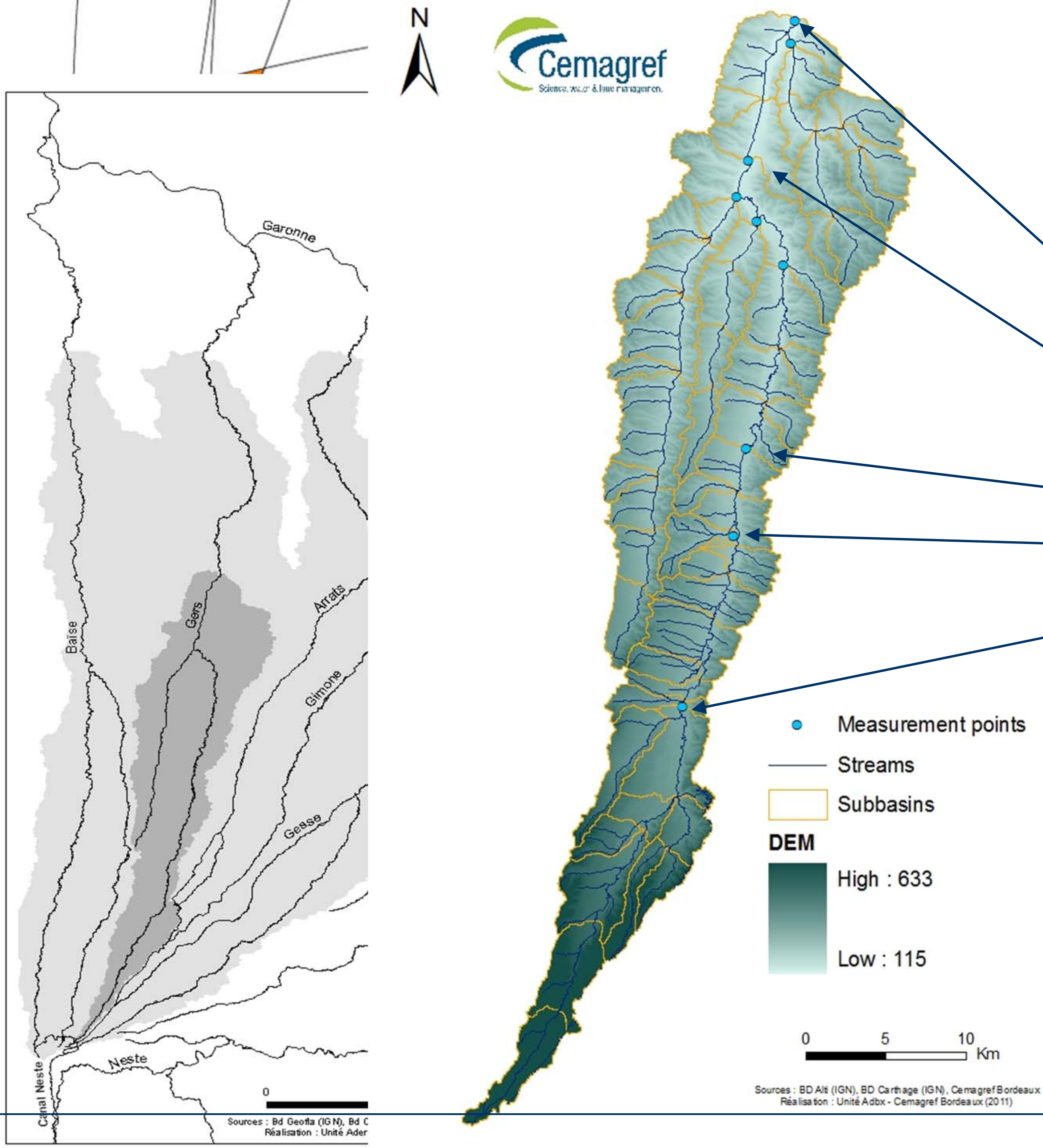
- Upstream part (UGRB) from Lannemezan plateau to the Roquelaure drinking water collection point

- 17 small rivers and streams (9000 km²) with extremely small water catchment areas (Côteaux de Gascogne)

- Hydrological processes characterized by superficial water transfers fed by shallow water tables with limited capacity

→ link canal (the Neste canal) created to improve water flows

Case study streams

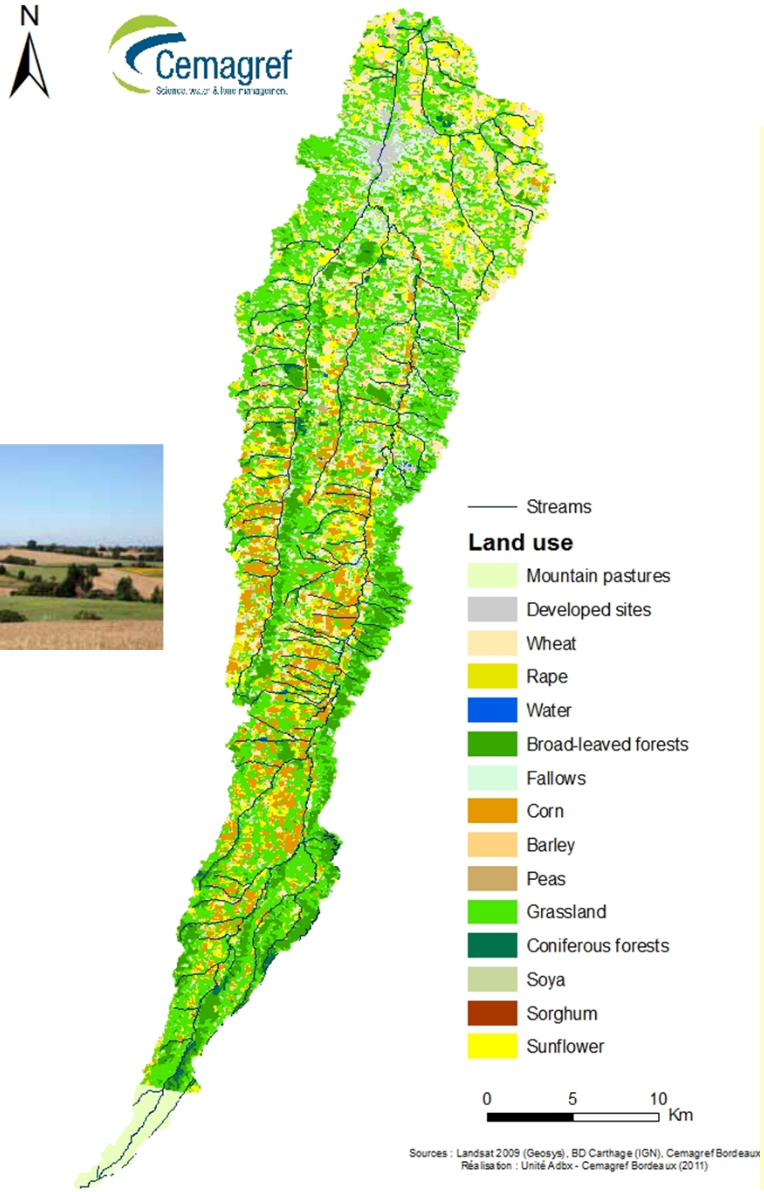


- 5 points for the abstraction of Drinking Water (30 000 hab.) with recurring problems of water quality relating to pesticides

- 65 % of water samples with concentrations > 0.1 µg/l for individual pesticide

- and 29 % with concentrations > 0.5 µg/l for total pesticides

Land use



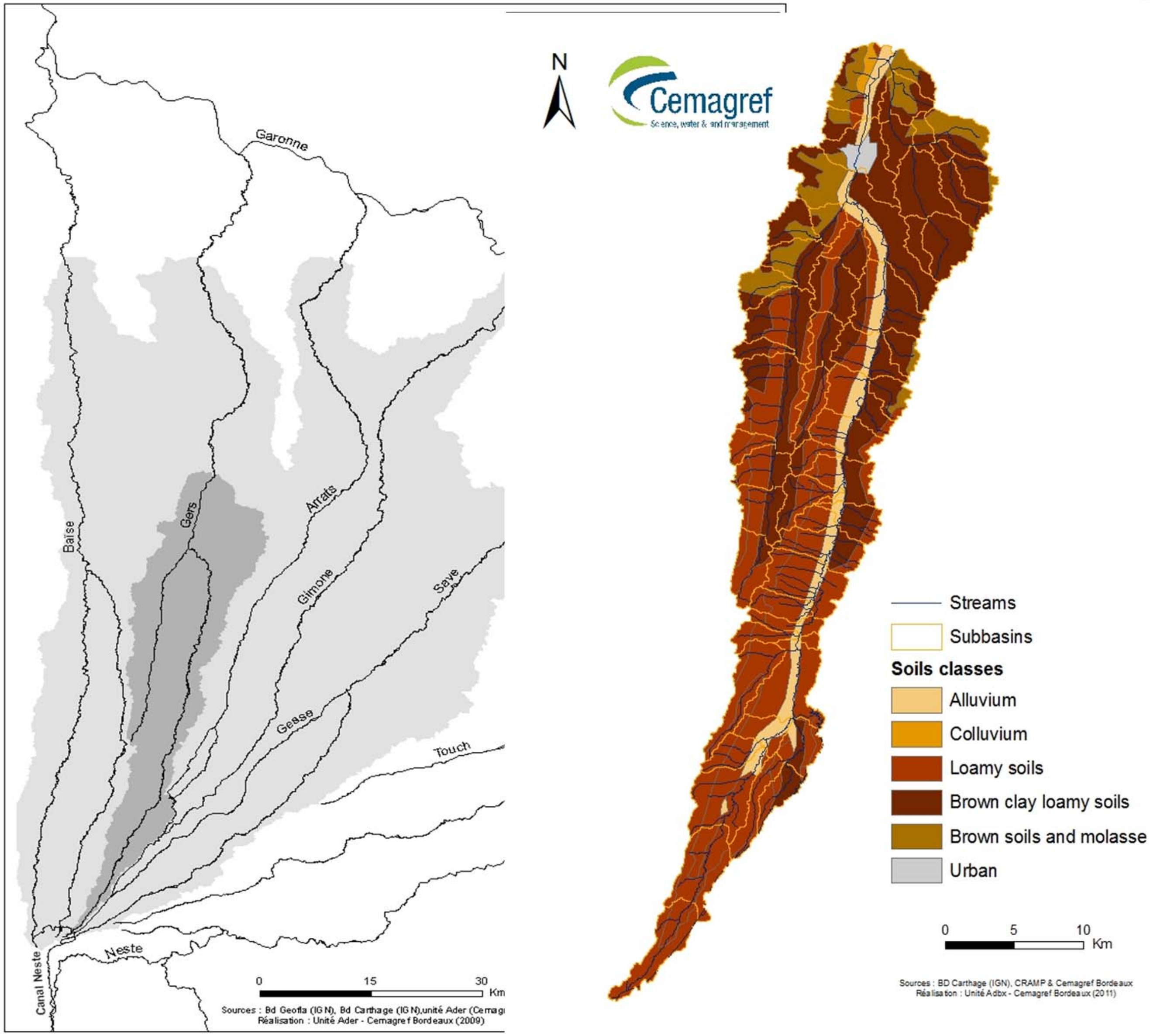
❖UGRB covers 47000 ha (470 km²) mainly dedicated to Agriculture 34000 ha (72% of the area)
- 700 farms on 55 communes

- mainly Cash crops
- Some Breeding activities suckler farming systems

80 % cropping pattern

- Corn for grains or silage southern part
- spring and winter wheat
- durum wheat
- Sunflower northern part
- Permanent and temporary grassland

Case study soils



❖Soils types of different characteristics such as

-Alluvium
-Colluviums
-Loamy clayey soils
-Clayey soils

Defining practices

❖Define areas with homogeneous characteristics of identified crop rotations (PCA, CA)

❖Crops rotations further improved from land cover data by applying

→Agronomical decision rules

→A random spatial function, producing as many HRUs as there are different types of crop rotations

and creating tables with practices (SWAT tables mgt1 and mgt2) for each HRU from average practices by crops constituting the crop sequence

❖Dates of management practices within periods are generated randomly from identified average values

Mitigation measures

Measures applied		Description	Implementation in the SWAT model
applied only on zones with	applied on the whole upstream area		
BS		**Riparian buffer strips:Grass strip with rye-grass**	
BS10_ZP	BS 10_GA	Buffer strips width 10m: 5meters on either side of the watercourse	Basis line scenario
BS10_ZP_ext		**Buffer strips width 10meters extended hydrographical network.**	Modification of the land use files (shape-files): Design of new polygons alongside the hydrographical network (Arc-GIS Buffer command) and accordingly modification of the parameter FILTERW
BS20_ZP	BS20_GA	**Buffer strips 2x10meters (BS 2x10m)**	
BS20_ZP_ext		**Buffer strips 2x10meters extended (BS 2x10m_ext)**	
MW_ZP	MW_GA	**Switching from chemical weeding to mechanical weeding. No herbicides application and tillage**	Modification of management parameters
LR_ZP	LR_GA	**Modification of crop rotation schemes (longer rotation with succession of 4 crops minimum)**	Modification of management parameters
CC_ZP	CC_GA	Catch crop during the inter-crop period (sowing of ryegrass between winter crops and spring crops)	Modification of management parameters
	SGL_GA	Increase of grassland/decrease of arable land. Switching from arable land (maize, wheat…) to temporary grassland (rye grass)	Modification of the land use files (shape-files)

- Measures proposed by the French Rural Development programm

  → Effective on water quality

  →As the most likely to be accepted and implemented by farmers

Effectiveness assessment using the SWAT model

- Assessment over a 25-years period with measures being applied each year

- Average values of pesticide concentrations calculated on the ten last years basis for the modeling period

- Effectiveness is considered in terms of the relative reduction of average concentration of total pesticides following measure implementation
Use of the values from the SWAT main channel output file (.rch)

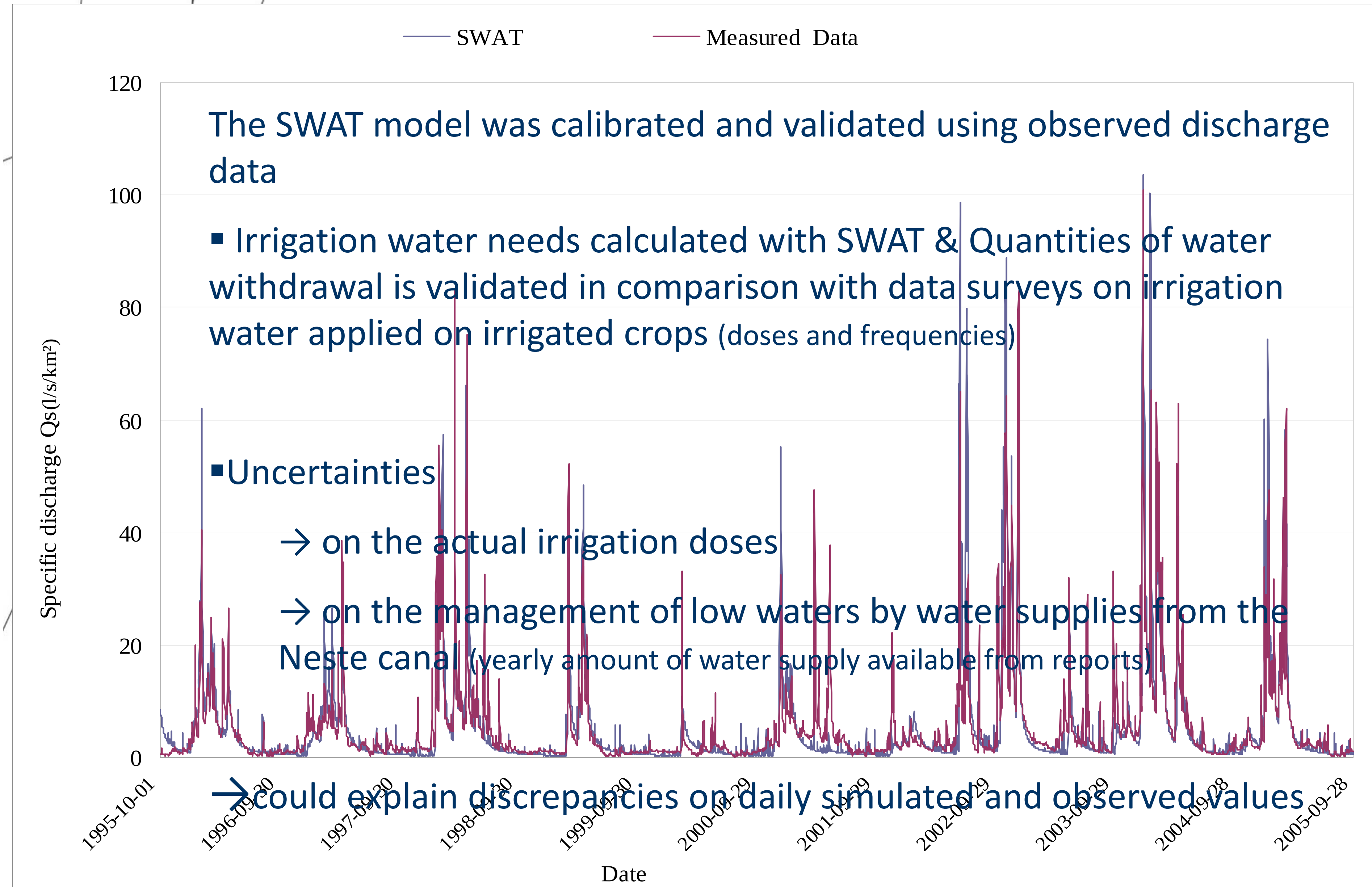
$$Effectiveness_{(\%)} = \left(1 - \frac{[C_s]_{\mu g l^{-1}}}{[C_0]_{\mu g l^{-1}}} \right) \times 100$$

$[C_0]_{\mu g l^{-1}}$ Average concentration over the ten last years of hydrological simulation

$[C_s]_{\mu g l^{-1}}$ Baseline concentration

- Variability in effectiveness between sub basin is calculated on the difference between inflows concentration and outflows concentration

Calibration/Validation for stream flows



The SWAT model was calibrated and validated using observed discharge data

- Irrigation water needs calculated with SWAT & Quantities of water withdrawal is validated in comparison with data surveys on irrigation water applied on irrigated crops (doses and frequencies)

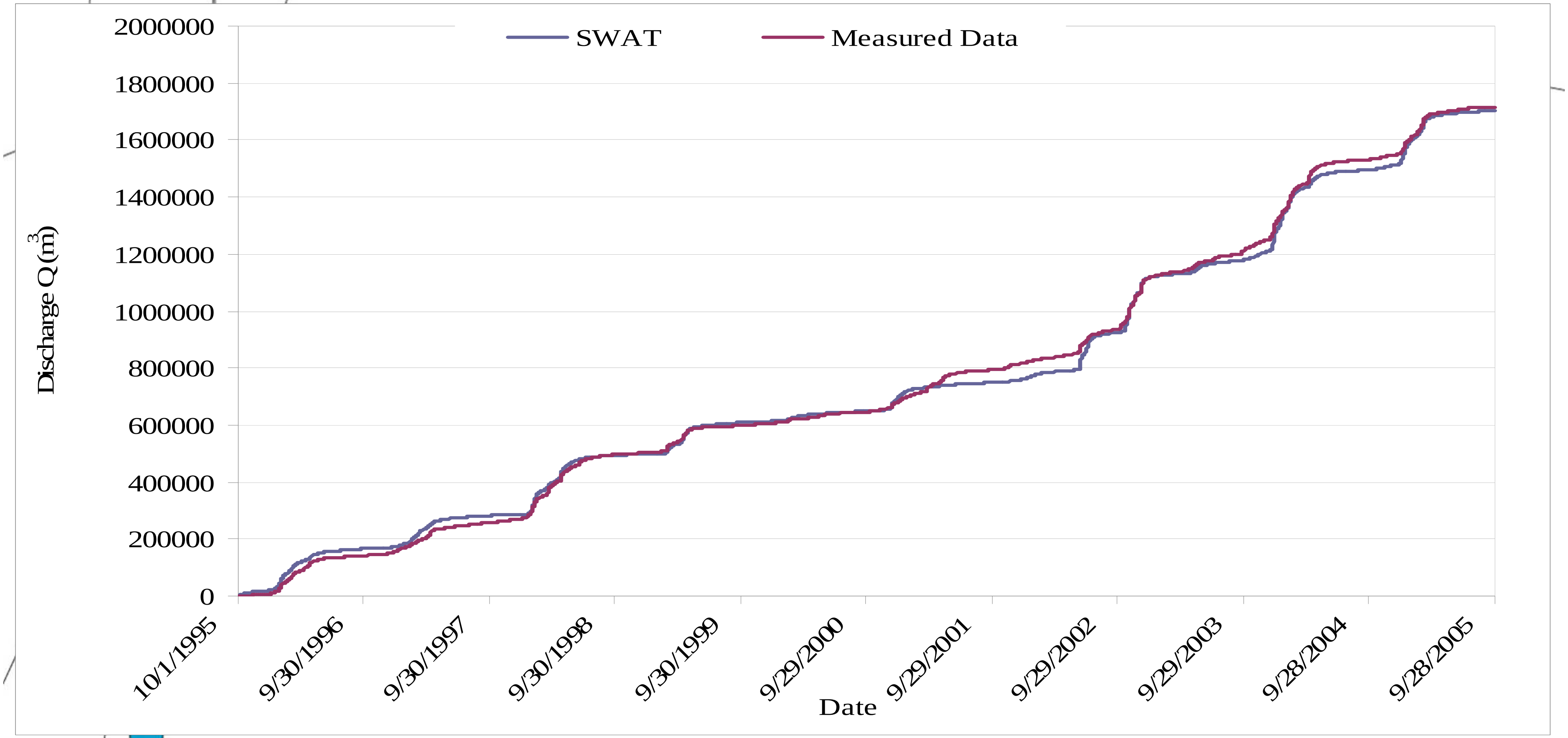
- Uncertainties

  → on the actual irrigation doses

  → on the management of low waters by water supplies from the Neste canal (yearly amount of water supply available from reports)

→ could explain discrepancies on daily simulated and observed values

Calibration/validation statistics for stream flows



		Calibration period (1985 to 1995)	Validation period (1995 to 2005)
R^2		0.80	0.72
NSI		0.65	0.63
Specific discharge Qs	Measured Qs_{obs}		5.44 l/s/km²
(liter per second per square km)	Simulated Qs_{cal}		5.40 l/s/km²

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Verification/Calibration of pesticides

- SWAT model has been implemented on the whole Côteaux de Gascogne zone then calibrated in order to reproduce total yearly pesticides concentration (1.2 µ g/l) at the upper stream watershed outlet (Roquelaure measurement point)

- Concentrations of pesticides analyzed on

- 4 measurements points alongside the Gers river (within the project)

- 5 points (tapping for Drinking Water Supply)

- 15 measurements points out on the main rivers of the Gascogne Côteaux zone from 2005 to 2008 (from another study by Cemagref)

→Frequency of sampling (4 to 5 measurements per year) to low for precise daily or monthly calibration and/or validation

→used nevertheless for verification by comparing on the same points of the streams, the ranking of the yearly average measured and simulated concentrations (total pesticides)

- Water analyses show that 4 molecules represent 80 % of the total pesticides concentration
    - Herbicides (Glyphosate, S-Metolachlor)
    - Insecticide (Carbofuran)
    - Fungicide from the triazole group (Tebuconazole)

- Set of Active Substances applied + frequency of their use (survey carried out on 50 farms within the watershed area) for each crop

- Spraying practices within the watershed are compared to the average practices set at the regional scale from a much wider sample of farms

→ Reduction of the number of applied active substances to the **molecules the most widely used + average dose** (arithmetic mean) applied by farmers

When a chemical class is widely applied

- fungicides (Sulfonylurea, Triazole and Strobilurin groups)
- herbicides with a mix of 3 or 4 active substances sulfonylurea

→ **new "Average Active Ingredient" (AAI)** for its physical and chemical properties (Koc , DT50 and solubility)

weighted by their relative concentration in the pesticide used *(for a mix of active substances)*

→we defined **an average application rate** calculated as the average application rate weighted by its frequency of use

→ Simulations are carried out for each of these 4 AAI
the sum of their daily concentrations simulated with SWAT used as results

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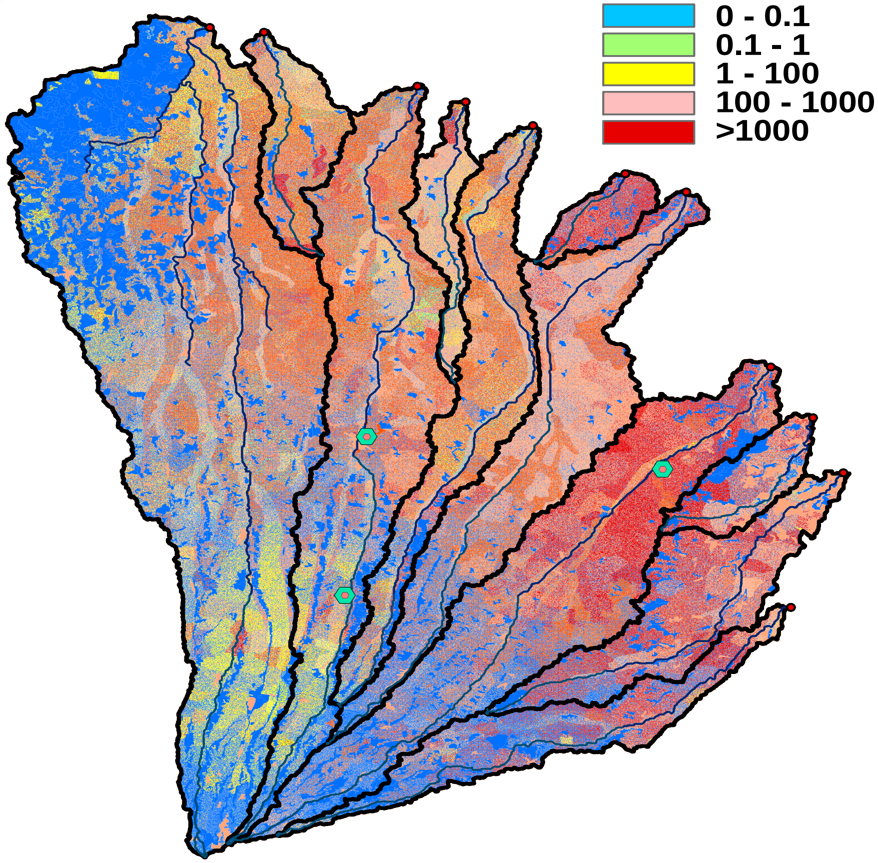
Pesticides run-offs modeling



Average yearly flows of total pesticides (mg ha^{-1} year^{-1}) from Hydrologic Response Units to main streams of the Coteaux de Gascogne. SWATModeling with basis line scenario - average on 15 years (1994-2009)

- Average simulated concentrations and measures differ sometimes heavily but

→the ranking of the simulated measurements points match exactly the ranking of measured points for all the points of the watershed

- Differences between simulated and measured concentrations do not imply that model calibration is wrong

because of the uncertainty on the measurements themselves (pertaining to their frequency and the number of values within a month and year)

Results for Effectiveness

Implementation	Scenario	Measures	Total concentration µgl-1(outlet)	Effectiveness (% reduction)
			1.2	Basis line scenario
Measure applied on the zones with priority	1.2	BS10_ZP_ext	0.85	29
	1.3	BS20_ZP	0.78	35
	1.4	BS20_ZP_ext	0.72	40
	2	MW_ZP	0.96	20
	3	LR_ZP	1.19	0.5
	4	CC_ZP	1.18	1
			1.2	Basis line scenario
Measure applied on the whole area of the upstream part	1.3	BS20_GA	0.66	45
	2	MW_GA	0.38	68
	3	LR_GA	1.18	1
	4	CC_GA	1.17	2
	5	SGL_GA	0.66	45

→ Pesticide loss may be effectively decreased by implementing measures

→ **Best results: restoration measures like riparian grass buffer strips**

varying however when applied in priority zones or in the entire GA area

→ **Switching from chemical weeding to mechanical weeding could have an immediate effect on pesticide loads**

enhanced when the measure is applied on the whole upstream area (MW_GA)

explained by the type of chemicals detected at high concentrations (mainly herbicides)

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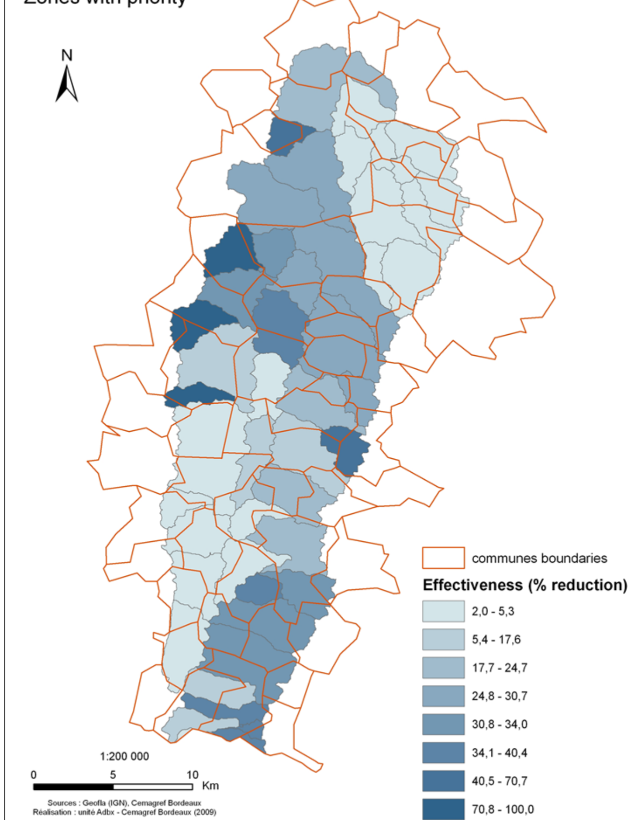
relative inefficiency of other changes in management practices (catch crops, changes in crop rotation schemes)

→Concentration objective of 0.5µgl^{-1} is never reached excepted for one scenario
→Combination of agri-environmental measures maybe more effective but need first to be assessed

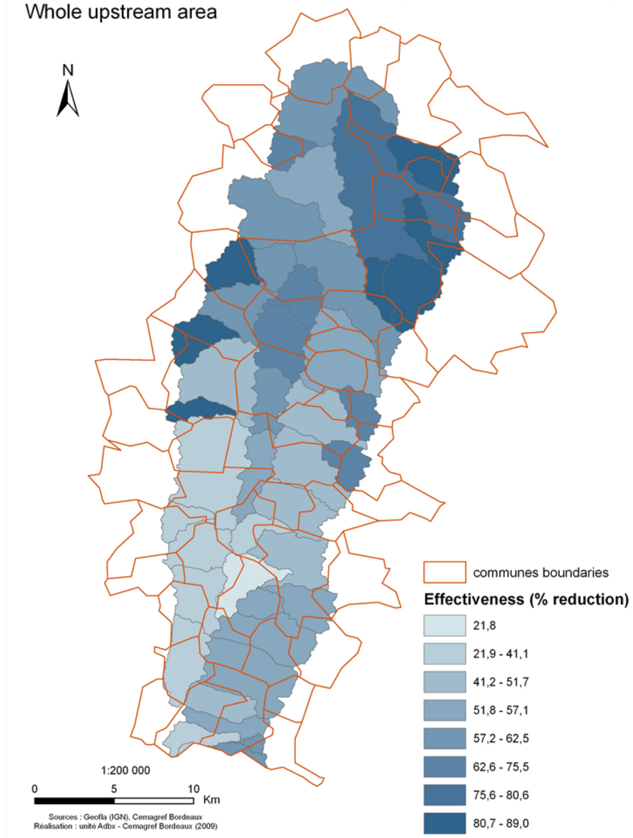
For a given measure, effectiveness nevertheless varies widely between sub basins within the watershed

Costs results

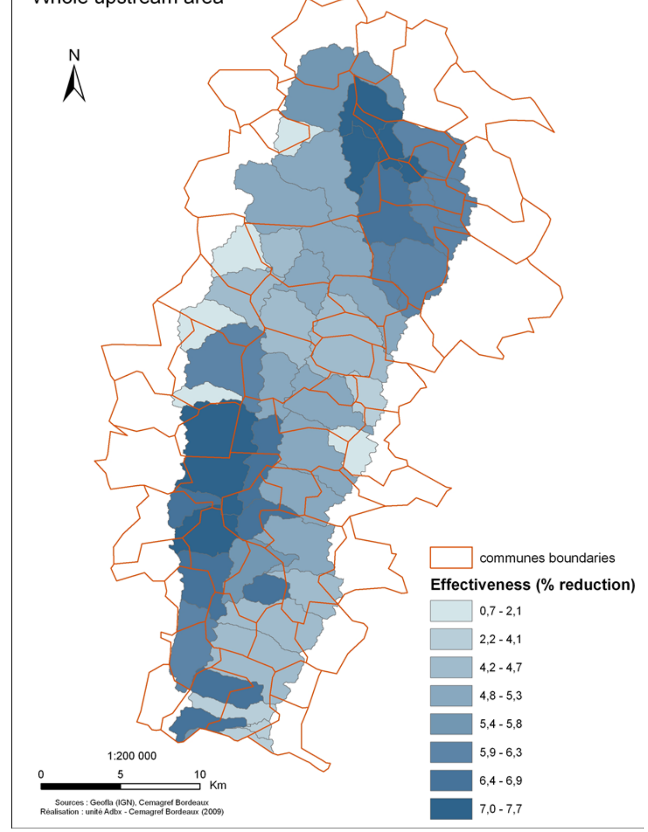
Effectiveness assessment at the sub river basin level
measure: riparian buffer strips 2x10m
Zones with priority



Effectiveness assessment at the sub river basin level
measure: switching from chemical weeding to mechanical weeding
Whole upstream area



Effectiveness assessment at the sub river basin level
measure: modification of crop rotation schemes
Whole upstream area



Costs of mitigation measures

Costs assessment

❖ Marginal costs of mitigation measures are not equal
Theoretically possible to obtain the same level of water pollution reduction at lower cost by shifting from high-costly measures to lower-costly measures

❖ The economic budgeting approach may reflect real word behavior
But budgets may not reflect efficient decisions from an economic perspective

→To derive a meaningful trade-off curve, all economic methodologies need to allow farmers the ability to interchange a variety of optional strategies into the decision making framework

❖The methodology of economic optimization
→more relevant for cost analysis of mitigation measures
→possibility it offers decision makers to substitute alternative strategies

Costs assessment

❖ Representative (average concept) or typical farms (modal concept) is usually the most satisfactory way of modeling farms

- potential bias from aggregating farm-level data or using average/ aggregate data at the farm level
- leaves out the spatial distribution of holdings

→ model farms together at the commune level as if they were a single mega-farm

- overstate the flexibility and co-ordination of agricultural productions
- considered appropriate for small areas like communes

→A model of Agricultural production at the commune level (HRU) is developed in Mixed Integer Linear Programming using GAMS software

Objective fonction : Max $f_c(X)$

$$f_c(X) = \sum_i \sum_p \sum_k (X_{i,p,k,c} * y_{ipk} * p_i - cv_{i,p,k} + inc_{k_2})$$

$$+ \sum_l \sum_p X_{l,p,c} * y_{l,p} * p_l - cv_{l,p}$$

For each c

c: commune (commune with at least 10% of its area within the catchment)
i: crop activities
l: livestock activities
p: level of practices intensiveness (intensive, average, extensive)
k: standard practices k_1 or with mitigation measure k_2
X_{ipkc}: acreage of the activity with crop i, intensiveness p and practice k (ha) within the commune c
y_{ipk}: yield of the activity [tons of grains or Dry Matter ha^{-1}] per crop, intensiveness level and practice type
p_i: price for grains (€.kg^{-1}) p_l: price for milk or meat (€.kg^{-1})
$cv_{i,p,k}$: variable costs of production by crop, level intensiveness and type of practice (€.ha-1)
inc_k: incentive (€.ha^{-1})

Bio-economic modelling

❖Levels of incentive required to make a measure appear in optimal modeled solutions considered to give the direct costs of its implementation

inc_{k_2}

→when the decision variable (activity with measure) appears in optimum solution, incentive and marginal cost cancel each other out

❖Marginal cost (Shadow cost) is regarded to represent the direct cost of the non optimal activity (with measure)

❖Marginal values indicate how far each activity with measure is from entering the optimal solution

but

Bio-economic modelling

→Doesn't not indicate what would be the optimal level of the activity if it did enter the solution

→nor does it indicate how the optimal level of other activities currently in the solution would be affected

❖To determine exactly what changes would occur

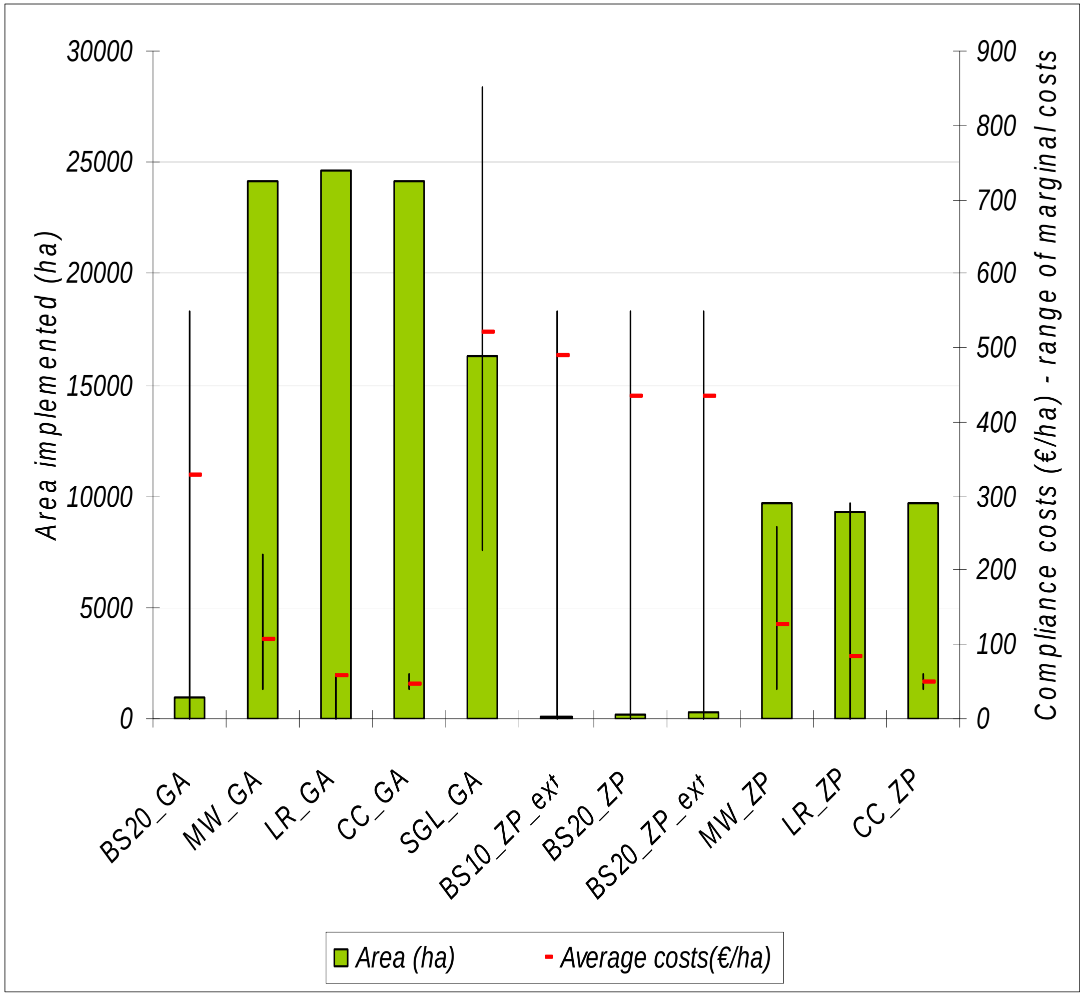
→ to alter the model and resolve it, what is done for increasing level of incentives

→ Integration of marginal costs > Total yearly costs
→Discounted sum of yearly costs > Total Cost over the implementing period

Costs results

Implementation	Scenario	Measures	Total costs (€) - 25 years period
Measure applied on the zones with priority	1.2	BS10_ZP_ext	1021979
	1.3	BS20_ZP	1002726
	1.4	BS20_ZP_ext	1795194
	2	MW_ZP	18136446
	3	LR_ZP	11372194
	4	CC_ZP	7012277
Measure applied on the whole area of the upstream part	1.3	BS20_GA	4601327
	2	MW_GA	37536281
	3	LR_GA	21238345
	4	CC_GA	15929465
	5	SGL_GA	125629621

- Wide range of marginal implementation costs
- Some measures, depending of their costs per ha implemented (catch crops) or the area implemented (buffer strips) are relatively less expensive to implement on the watershed level



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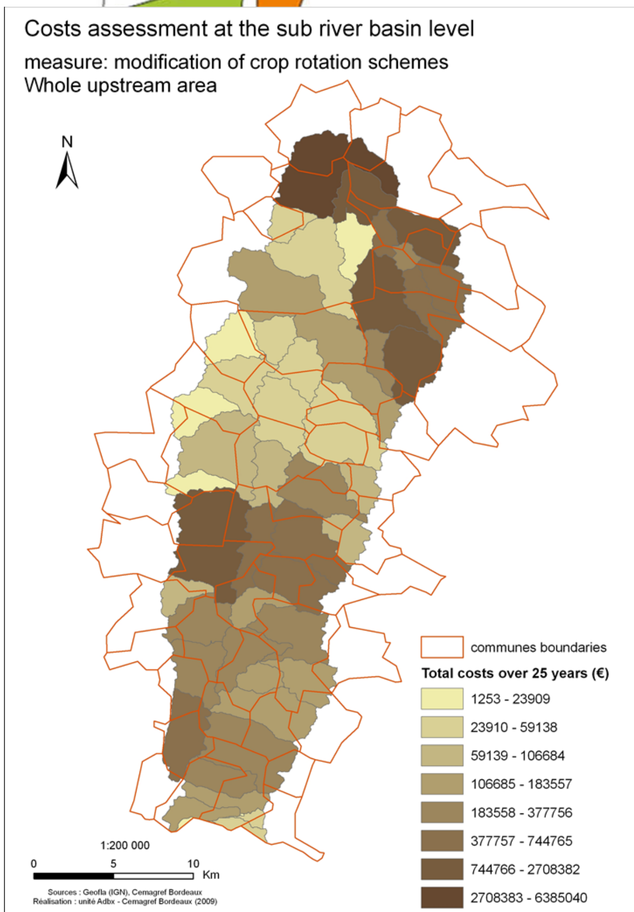
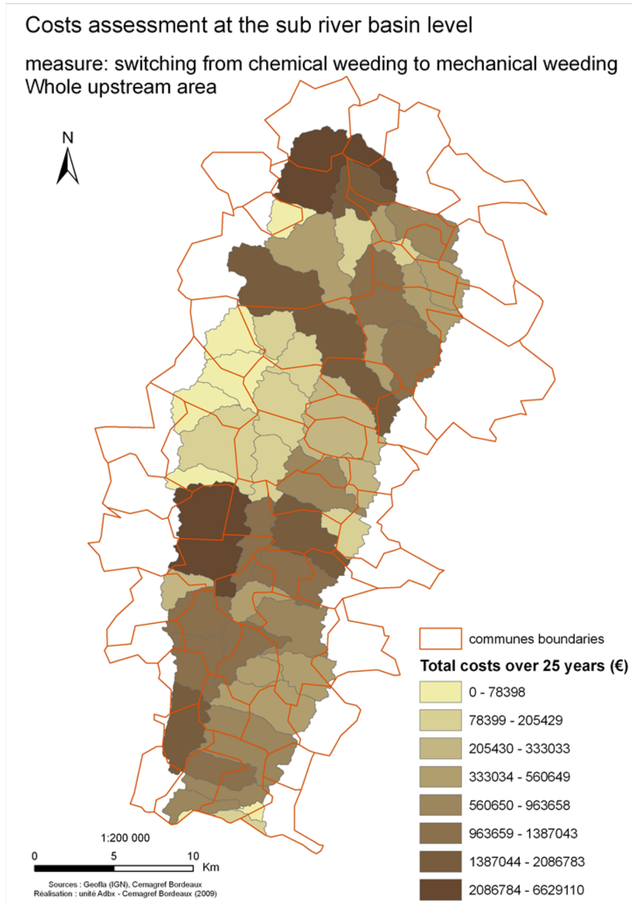
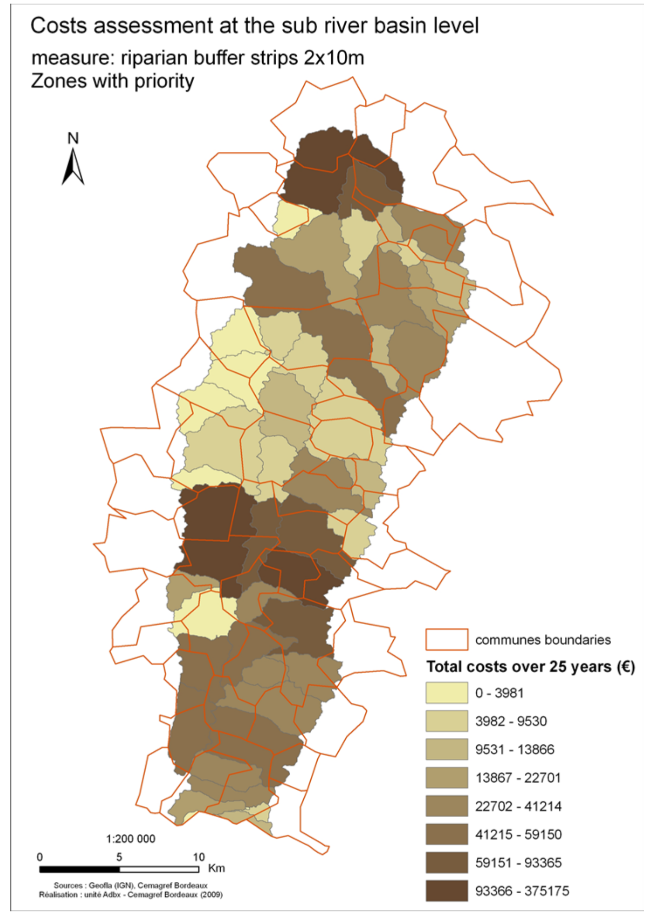
Costs results





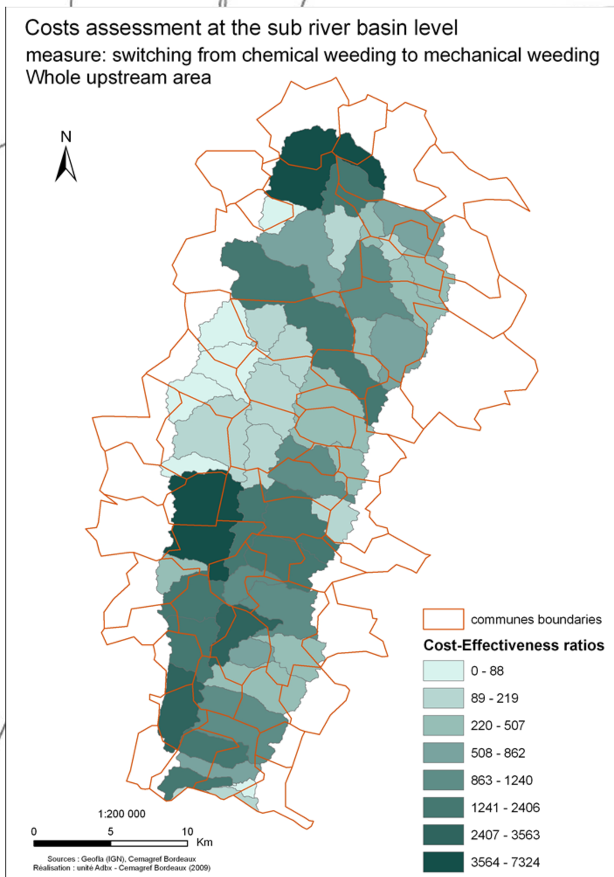


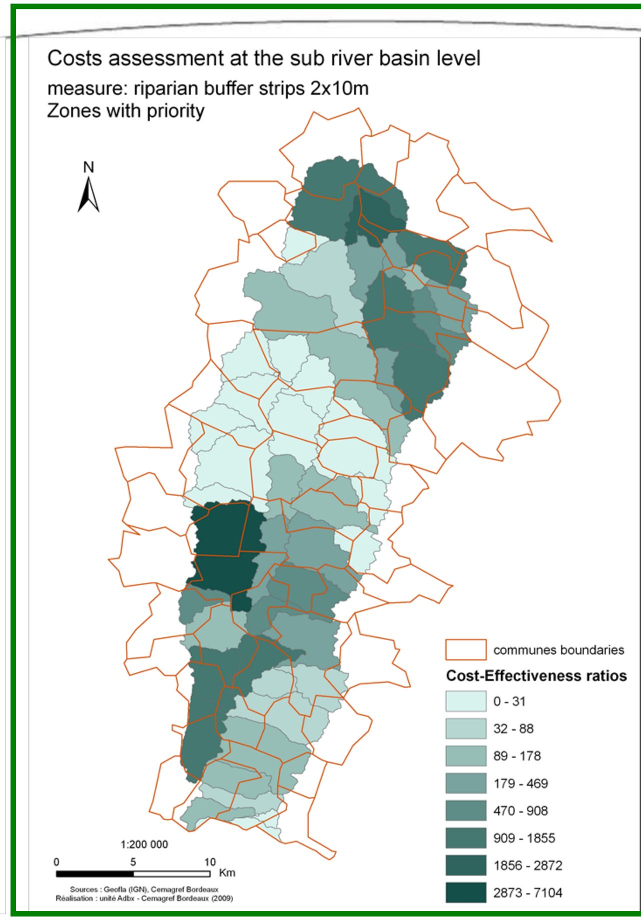
For a given measure, calculated marginal costs and total costs vary widely between communes as changes are applied to different crops, rotation sequences and farming systems.

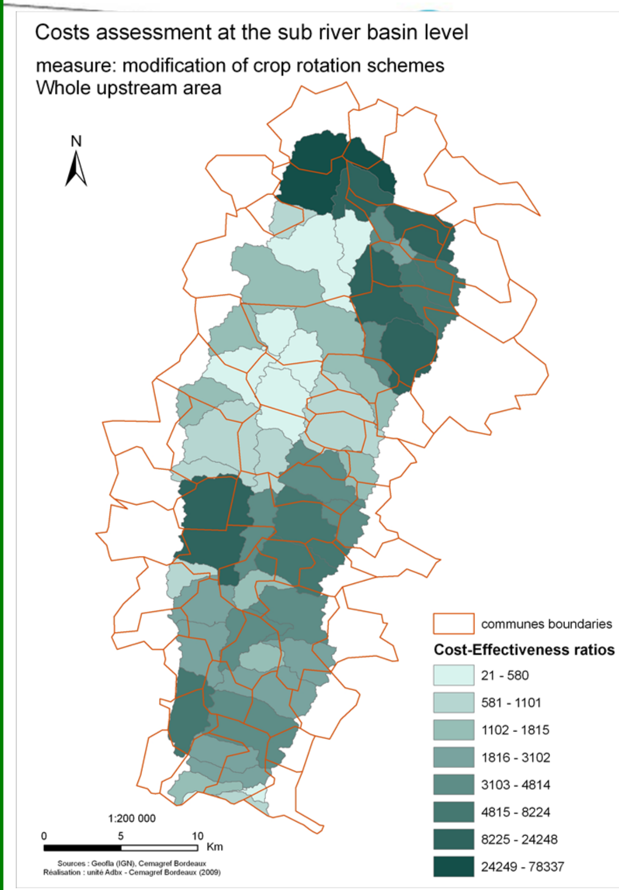
Cost Effectiveness Analysis

Implementation	Scenario	Measures	Total concentration µgl-1(outlet)	Effectiveness (% reduction)	Total costs (€)	C(k€)/E ratios
			1.2	Basis line scenario		
Measure applied on the zones with priority	1.2	BS10_ZP_ext	0.85	29	1021979	35
	1.3	BS20_ZP	0.78	35	1002726	29
	1.4	BS20_ZP_ext	0.72	40	1795194	45
	2	MW_ZP	0.96	20	18136446	907
	3	LR_ZP	1.19	0.5	11372194	22744
	4	CC_ZP	1.18	1	7012277	7012
			1.2	Basis line scenario		
Measure applied on the whole area of the upstream part	1.3	BS20_GA	0.66	45	4601327	102
	2	MW_GA	0.38	68	37536281	552
	3	LR_GA	1.18	1	21238345	21238
	4	CC_GA	1.17	2	15929465	7965
	5	SGL_GA	0.66	45	125629621	2792

- Riparian grass buffer strips
- Switching from chemical weeding to mechanical weeding - Changes to grassland
- Longer rotation schemes – Catch crops







❖For a given measure, CE ratios of implementing measures vary widely between communes as a result of Effectiveness and Cost variability within the watershed

→Mechanical weeding in replacement of chemical weeding could be then sometimes more Cost-Effective than Grass buffer strips depending of the location where the measure is applied

Conclusion

Objective: find the changes of crops and practices that will contribute most to achieving goals at minimum costs

❖ Useful for policy analysis

→By integrating the environmental and the economic issues at diverse spatial and time scale

→Profitably replace more classical approaches based on pressure indicators allowing the integration of the dynamics of the agro-hydrological systems

→Better target the implementation of measures and financial incentives to farmers where appropriate

❖ CE analysis: Simple educational and communication tool summarizing the outcomes in a single quantifiable indicator for participatory approaches (integrated information needed)

Thanks for your attention

Gracias por su atención

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Uncertainty

❖ Uncertainty at each step of the analysis

- Uncertainty surrounding environmental goal and parameters
- Uncertainty surrounding the sources of pollution (PS, NPS)
- Uncertainty surrounding the choice of the measures defined by Science
- Uncertainty about the placement for implementing the measures
- Uncertainty surrounding the Costs and Effectiveness of mitigation measures
  - → Sensitivity Analysis with SWAT and Bio economic model