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Potential of artificial wetlands for removing pesticides from water in a cost-effective framework[1]

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Abstract

The purpose of this paper is to analyze the implication of wetland construction for the cost-effective design of a pesticide charge. A model is developed in order to show that, for a given target, the introduction of wetland construction can reduce overall abatement costs and can lower the input charge asked to the farmers. This result remains true as long as the cost of constructing a wetland is not too high. A numerical illustration is carried out in order to simulate pesticide regulations in a wine catchment in North-East of France.

Keywords: water policy, constructed wetlands, agricultural pollution regulation.

J.E.L. classification numbers: Q25, Q58, K32.

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1 Introduction

In the European Union, the water policy is mainly driven by the Water Framework Directive (WFD) of 2000. One of its main targets is to work toward an environmental quality illustrating the best trade-off between economic and ecological interests. One consequence is that member states are looking for economic instruments allowing to reach a pre-defined standard of water pollution at the lowest cost possible. Wetlands play a crucial and growing role since they can constitute one of the cheapest means to be used, in combination with classic regulation instruments like charges on polluting inputs, in order to achieve environmental quality standards. For instance, in Sweden, one of the measures implemented by the Government in order to reduce the excessive nutrients that contribute to the eutrophication of the Baltic Sea was the establishment and restoration of wetlands.[1]

The point of departure of our paper is that the lowest cost possible means of improving water quality could involve the use of wetlands. But what are the implications in terms of water pollution regulation? The WFD also promotes the extensive use of economic incentives like input charges. This means that governments have to combine economic instruments consisting in giving incentives to reduce the use of polluting inputs and wetlands restoration. What will be the effect of using wetlands on the input charge and on the farmers' abatement effort? This is the main question that we want to investigate in this work. In order to answer, we propose to build a model underlying the main forces that are at work. We will keep this model as simple as possible in order to be able to illustrate it by using some "real" data.

Söderqvist (2002) explained that *"wetlands can reduce nutrients (nitrogen and phosphorus) in water by denitrification, sedimentation, and plant uptake, although nutrient reduction seems to vary substantially among different types of wetlands and climatic conditions"*. Taking the fact that wetlands have a significant capacity to reduce pollution as a point of departure, Byström (2000) estimated a replacement value for wetlands in Sweden in order to assess how effective wetlands are, relative to other abatement measures, in providing low cost reductions of nitrogen pollution. In order to do so, he defined such a value as the savings in total abatement costs that are made possible by using wetlands as an abatement measure. He noted that he does not consider other values of wetlands such as recreational ones or flood control.[2] In his work, Byström (2000) was looking for the cost-effective reductions of nitrogen load to the Baltic Sea among nutrients application reduction, land usage change and restoration of wetlands. More recently, Herberling, Garcia and Thurston (2010) proposed to study the possibility of incorporating the

[1] See Gren, Elofsson and Jannke (1997), for instance.

[2] The reader is referred to Brander et al. (2006) for a complete survey related to economic valuation of wetlands.

use of wetlands in water quality trading programs in order to meet national wetlands goals and advance these programs. The main contribution of our work with respect to this literature is to study the implication of wetlands for the cost-effective design of an input charge. In the case of nitrate pollution this consideration is of wide interest since several European countries such as Finland, Austria, Sweden, Denmark or the Netherlands implemented charges. But Bel et al. (2004) showed that the tax on fertilizers had almost no impact on fertilizers sales, mainly because of their rate being too low. In our framework, the charge will be assumed to be at the "good" incentive rate.

A wide range of the most recent literature related to the question of wetlands ability of reducing water pollution deals with uncertainty aspects. For instance, Paulsen (2007) discussed how uncertainty influences a farmer's decision-making process and how different information structures might affect the private decision to change land usage from agricultural, or an other usage, into wetlands. She took one of Byström's paper (2000) implications, according to which a subsidy established for wetland construction does not have the same effect in southern Sweden as in other regions of the country, as a point of departure in order to analyze how uncertainty can explain these differences. Crépin (2005) studied the incentives (in the form of contracts) for wetlands creation in an asymmetrical information context. All these works are primarily concerned with the wetlands restoration by agents (farmers) themselves. Our main message is quite different since it relies on the fact that the regulation of water pollution should not be considered independently of other regulations such as the size of wetland restored by a regulator (and not an agent). It is why we will rather focus on a deterministic setting with perfect and complete information of the regulator. In a setting where the regulator can set the level of the input charge knowing the reaction of the polluter, the potential of wetlands for cleaning water in a cost-effective framework must be the worst one and if this potential is confirmed, it will also be the case in an incomplete information setting. Besides, Byström, Andersson and Gren (2000) already addressed the questions of the uncertainty of wetland's abatement capacity and of the impact on the overall uncertainty of pollution. They showed that wetlands remain economically rational to use. Furthermore, in order to lead a complete numerical illustration in an uncertain setting, we would need more data from scientists of other disciplines. It is why we decided to leave the question of the uncertainty of the wetland abatement capacity to a future multidisciplinary work.

All the papers previously quoted are primarily concerned with denitrification and natural wetlands. In the chemistry literature, Grégoire et al. (2009) explained that *"among the communications devoted to artificial wetlands since 1973–2007 (i.e., 32%), 39% reported on the fate of the nutrients (nitrogen and phosphorus) in the hydrosystem, 11% dealt with the fate of* *the heavy metals, 8% are devoted to the study of dairy at the farmer scale and only 2% dealt with the pesticides fate in the environment. Since the last 7 years (i.e., 2000), the proportion of the publications concerning pesticides fate in the artificial wetlands increased (Schulz 2004) and reached 8% of the publications devoted to the artificial wetlands and natural wetlands."* Our numerical illustration is based on pesticide pollution of water and on its assimilation by an Artificial Wetland (AW). We define an AW as a wetland constructed on purpose by a regulator, with an impermeable bottom.

European policy concerned with pesticides begun in 1979, then evolved until the Council Directive 91/414/EEC, which framed the evaluation, the marketing and the use of pesticides (herbicides, insecticides, fungicides etc.) in plant protection in the Community. However consumption and use of pesticides have not decreased in the European Union. Thus the Thematic Strategy on the sustainable use of pesticides was adopted in 2006. This Strategy leads to the Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides. This Directive encourages the use of economic instruments: *"Economic instruments can play a crucial role in the achievement of objectives relating to the sustainable use of pesticides. The use of such instruments at the appropriate level should therefore be encouraged while stressing that individual Member States can decide on their use without prejudice to the applicability of the State aid rules"*. It is why we will take the use of an economic instrument such as an input charge as a point of departure and we will study how this instrument is likely to depend on wether an AW is constructed or not. This is consistent with our assumption according to which the regulator perfectly knows the cost functions of the farmers: in such an ideal context, the input charge is one of the best economic instrument to be used. The rate applied in real case studies is too low to be efficient. We will rather reason on an efficient rate.

To sum up, our main aim is to analyze the implication of considering AW construction as a new regulation tool on the cost-effective design of a pesticide charge. In order to do so, we constructed a model easily tractable for a numerical illustration with some "real" data relating to AW capacity of pesticides abatement, issued from scientists of other disciplines.

An AW acts as a natural filter. Both bacteria and plants having colonized the AW participate to the pollution assimilation. The amount of pollution assimilated depends on how long (in hours) the water lie in the AW; this duration is strongly linked to the size of the AW. In a static[3] framework, the efficiency of an AW thus depends both on the mass of pesticides into water when it enters into the AW and on the size of the AW. It is exactly the same running as for

[3] A dynamic setting with a time step of hours does not make sense in economics.

a natural wetland (see for instance Byström, 2000). The difference in our framework is that we assumed that the farmers are not able to construct an AW in order to reduce pollution because of the opportunity cost of land being too high. We made this assumption because we wanted to underline the fact that water pollution regulation can no more be considered independently of other regulations such as AW construction. As a consequence, in our framework, the regulator is either able to increase or decrease the size of the AW.

We considered a regulator who controls the water pollution in the way recommended by the WFD: a target mass of pesticides has to be attained at the lowest cost possible, within the framework of the "polluter pays" principle.[4] This means that the farmers have to bear the costs of reducing pollution toward the target mass[5] and that the regulator is not a profits maximizer. In order to investigate how the consideration of the construction of an AW can affect the pesticide charge used in order to regulate water pollution, we decided to compare two versions of the model: the version in which the regulator additionally constructs an AW in order to reduce pollution and the other one in which it does not. We showed that the consideration of AW construction possibility can reduce the proportional charge on pesticides used that has to be implemented and thus the effort that is made by the farmers in terms of input used reduction made in order to reach the target mass of pesticides in water. This result is illustrated with a case of fungicides pollution by wine-growers. Its validity domain strongly depends on the relationship between the cost of constructing the AW and the reduction of effort implied for the farmers.

We will present our model in section 2. In section 3, we will study the benchmark case in which the regulator does not construct an AW in order to reduce pollution. Section 4 will be devoted to the case in which it is constructed. In section 5, we will compare the two cases in order to investigate the implications on the charge that has to be implemented within such a framework, and thus on the effort of pollution abatement made by the farmer. Finally, in section 6, we will develop a numerical illustration applied to a wine catchment area located in North-East of France. We will conclude this work in section 7.

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[4] For the purpose of the numerical illustration, in this work, we will concentrate on a mass of pesticides although the WFD is more concerned with a concentration. But if we exclude the questions of hydraulic differences, it is very easy to turn to a concentration since it is the ratio of this mass with the volume of water concerned.

[5] Within such a framework, the target mass of pesticides can be socially optimal although the agency does not have the information about the marginal damage of this pollution. For instance, in Europe, the Good Status of the WFD has been defined during a bargaining process between environmental protection associations, polluters and water users.

2 The model

We consider a watershed with a fixed number n of farmers and a regulator. The regulator wants to reduce pollution from pesticides used by farmers in order to reach a water quality target in the outlet of the watershed. We assume that there are two possible ways of reducing pollution:

- on the one hand, the farmers are supposed to be able to reduce the amount of pesticides used if the regulator gives them some economic incentives,
- on the other hand, the regulator can construct an AW that is able to remove pesticides molecules from water.

In order to keep the model easily tractable for a numerical illustration, the farmers are assumed symmetrical. x denotes the amount of pesticides used by a farmer. $\delta := \bar{x} - x$ is the pesticide used reduction operated by the farmer with respect to the one corresponding to his optimal running, $\overline{x}$. The pesticides used reduction δ has a cost[6], $\kappa(\delta)$, which reflects the change in the farmer's profits resulting from this reduction. This cost is assumed to increase with the amount of pesticides removed, at an increasing rate (it is convex): $\kappa_\delta > 0$ and $\kappa_{\delta\delta} > 0$.[7] Furthermore, no reduction induces no cost, $\kappa(0) = 0$; small reductions are not very costly, $\lim_{\delta \to 0} \kappa_\delta = 0$; but large ones are disheartening, $\lim_{\delta \to \overline{x} - \underline{x}} \kappa_\delta = +\infty$. $\delta \to 0$ means that the amount of pesticides used is at its maximum, $\overline{x}$, and $\delta \to \overline{x} - \underline{x}$ that it is at its minimum one, $\underline{x}$.

We also assume that the mass of pesticides in water, M, is proportional to the total amount of pesticides used: $M := \alpha X$ where $X := nx$ is the global amount of pesticides used at the catchment level and $\alpha \in [0, 1]$ is the transfer coefficient of the pesticides used into the water; $1 - \alpha$ is usually called the natural assimilative capacity.

The regulator is assumed to own the land located downstream with respect to the farmers' fields. As a consequence, it can decide to construct on these lands an AW of size S, in order to eliminate some pesticides contained in water at the outlet of the watershed under consideration. We assume that the suitable land area that can be converted into an AW is such that the size can not be higher than $\overline{S}$, since the regulator does not hold infinite property rights on lands. The construction of an AW has a cost that is assumed to depend on the size converted: $c(S)$. It is increasing, $c_S > 0$, and convex, $c_{SS} > 0$, and there is no cost when no AW is constructed:

[6] In order to keep the model easily tractable for a numerical illustration (no game theory framework with heterogeneous agents), this cost function is assumed to be the same one for all farmers.

[7] Subscripts of functions indicate partial derivatives.

$c(0) = 0$. Furthermore, small constructions are not very costly, $\lim_{S\to 0} c_S = 0$, but large ones are disheartening, $\lim_{S\to \overline{S}} c_S = +\infty$.

Concerning the physical process behind the reduction of the pollution with pesticides thanks to the construction of the AW, we are going to assume that the quantity, q, of pesticides assimilated by an AW of size S, depends both on the total mass of pesticides in water at the exit of the AW, M, and on this size: $q := q(S, M)$. We expect that q is increasing with the size of the AW (at a decreasing rate: $q_{SS} < 0$) and also with the mass of pesticides (q_M and $q_S > 0$). q_M can be interpreted as the efficiency of a pre-determined AW with respect to the pesticides assimilation; it is positive and we assume that the mass of pesticides assimilated by the AW increases less than one unit when the mass of pesticides entering into it increases in one unit: $1 > q_M > 0$. No molecule of pesticides induces no assimilation and neither does no AW construction: $q(0, M) = q(S, 0) = 0$. The total size of AW available, $\bar{S}$, is assumed so high that, next to this point, each additional unit of AW becomes inefficient, $\lim_{S\to \overline{S}} q_S = 0\ \forall X > 0$, and when no AW is constructed, the efficiency of constructing the first unit is assumed strictly positive, $\lim_{S\to 0} q_S > 0\ \forall X > 0$.[8]

To sum up,

- when the AW is not constructed, the mass of pesticide in water is proportional to the quantity applied by the farmers: αX,
- and when it is constructed, the mass of pesticide in water is equal to the previous one minus the assimilation of pesticides by the AW: $\alpha X - q(S, \alpha X)$.

The target mass of pesticides is denoted $\overline{TM}$. The pollution induced by the minimum mass of pesticides used is assumed always lower than the target mass: $\overline{TM} > \alpha \underline{X}$ where $\underline{X} := n\underline{x}$. Furthermore, the AW is assumed to be unable to assimilate the amount of pesticides corresponding to the farmers' maximum profits up to the target mass: $\alpha \overline{X} - q(S, \alpha \overline{X}) > \overline{TM}$ $\forall S > 0$ where $\overline{X} := n\overline{x}$. As a consequence, the pollution induced by the maximum mass of pesticides used is always higher than the target mass: $\alpha \overline{X} > \overline{TM}$.[9] This assumption, combined with the symmetrical one, is in phase with the WFD setting since the target mass, $\overline{TM}$, is negotiated between farmers and environmental protection associations. The assumption on the target mass without AW construction also implies that: $\alpha \underline{X} - q(S, \alpha \underline{X}) < \overline{TM}\ \forall S$.

[8] All these assumptions were approved by some soil experts, members of the LIFE Environment ARTWET project.

[9] This assumption doesn't work for pesticides with very low adverse effects in aquatic ecosystems where the pollution corresponding to farmers' maximum profit could be below the targeted mass. A a consequence, our results won't fit to such uncommon kind of pesticides.

Remark 1 *Our assumptions on $\kappa(\delta_i)$ insures that the minimum of this function is reached at $x_i = \overline{x}$.*

Remark 1 tells us that when no regulation is implemented, the farmers aiming at minimizing the costs of their pesticides used reduction will choose to use the amount of pesticides maximizing their profits. Since we assumed that $\alpha\overline{X} > \overline{TM}$, the target mass can not be reached without some form of regulation of water pollution like a charge on pesticides used. Within our framework, it is the regulator that will pursue this aim. In the benchmark case, this regulator will only implement such a fiscal scheme. We will then consider another case in which an AW can be constructed in order to reduce the mass of pesticides in water. In this latter case, since we assumed that the total AW size can not be sufficient in order to reach the target ($\alpha\overline{X} - q(S, \alpha\overline{X}) > \overline{TM}\ \forall S > 0$), the regulator will also have to implement a new fiscal scheme. We make these assumptions in order to concentrate on the impact of an AW construction on the proportional fiscal scheme in more details. From the best of our knowledge, no paper concentrates on this aspect.

3 The benchmark case: the artificial wetland is not constructed

In order to better underline the implications of AW construction, we propose to build a very basic model consisting in three steps. But since these steps reflect a decision process, they can be considered so closed in time that it is possible to ignore discounting effects.

- In the first step, the regulator chooses the proportional charge on pesticides use, τ,[10] that minimizes the sum of the farmers' costs needed in order to achieve the target mass.
- In the second step, each farmer chooses the amount of pesticides that minimizes his costs, which then include the level of money levied through this proportional charge. In this work, we don't enter into the description of the decision process behind the pesticides used reduction.
- In the third step, the regulator balances its budget through transferring the amount of money collected in the previous step as a lump-sum transfer back to the farmers who are assumed myopic, i.e. they do not anticipate the exact value of this lump-sum transfer. We justify the requirement of a balanced budget with respect to charge/lump sum payments for water pollution by a "water pays water" principle. Furthermore, this will allow us to lead a complete cost-effectiveness analysis.

[10] It is the same one for each farmer since they are assumed symmetrical.

We are going to solve this model backward.

In the **third step** and once the target mass had been reached, the total amount of money collected with the charge on pesticides used is redistributed, in an equal way, as a lump-sum transfer, $\widetilde{LS} = \frac{\tau X}{n}$, to each farmer. The regulator is assumed to be a public agency that does not want to make profits; it is why it redistributes the money collected to the agents that we have in our model: the farmers. We assume all along this paper that there are no regulation costs.

The lump-sum transfer could induce a strategic behavior of the farmers consisting in not reducing the amount of pesticides used. But we assumed that they are myopic and thus unable to anticipate the amount of the transfer, i.e. the lump-sum appears as a constant in the objective function of the polluter. What about the European "polluter pays" principle? It is still at work since even if the charge collected in order to reduce pesticides used is given back to the farmer, he has to incur the costs of reducing his pesticides use up to the level allowing to reach the target $\overline{TM}$.

In the **second step**, each farmer takes the charge rate as given since it is fixed by the regulator. Furthermore, since the farmers are assumed myopic, they are unable to anticipate the exact value of the lump-sum transfer. The program that each farmer solves is thus the basic following one:

$$\min_x \kappa(\delta(x)) + \tau x - \widetilde{LS}$$

where $\delta(x) = \overline{x} - x$.

Remark 2 *The objective function is strictly convex since* $(-\kappa_\delta + \tau)_x = \kappa_{\delta\delta} > 0$.

The solution x^* of this program, where the superscript $*$ denotes the solution of the benchmark case, satisfies a classic first order condition according to which marginal cost of abatement equalizes the charge on pesticides:

$$\kappa_\delta^* = \tau \tag{1}$$

Lemma 1 *(i) The total amount of pesticides used in the catchment area exists, is unique and decreases with the charge rate.*
(ii) When the charge rate is zero, the amount of pesticides used in the catchment area is maximum and when the charge is very high, it goes to its minimum.

It directly follows from this lemma that $X^*(\tau) \in [\underline{X}, \overline{X}]$.

Finally, in the **first step**, the regulator chooses the proportional fiscal scheme τ such that the target mass is reached:

$$\alpha X^*(\tau) = \overline{TM}$$

We assumed that it has got a perfect and complete information but no profits maximization objective. As a consequence, it is perfectly able to anticipate the best reply of the farmers to this charge, $X^*(\tau)$.

Furthermore, our assumptions on the target mass, $\alpha\overline{X} > \overline{TM} > \alpha\underline{X}$, insure that $X^*(\tau) \in]\underline{X}, \overline{X}[$ and the interiority of the charge rate, i.e. $\tau^* \in]0, +\infty[$, then directly comes from Lemma 1.

Proposition 1 *At the unique solution of the benchmark case* (X^*, τ^*),

(i) $\frac{n\kappa_\delta^*}{\alpha}$ *denotes the marginal cost of removing one unit of pesticide from water.*

(ii) The global amount of pesticides used in the catchment area is decreasing with the transfer coefficient of pesticides into water and increasing with the target mass.

(iii) The cost-effective charge on pesticides is increasing with the transfer coefficient and decreasing with the target mass.

We now turn to the study of the solution of the same problem in which we add the AW construction.

4 The new condition of cost-effectiveness when an artificial wetland is constructed

As we explained in the introduction, there is some empirical evidence in favour of the construction of AW in order to clean up water from the pesticides that it contains. When the regulator is taken this possibility into account, it is mainly the first and the third steps of the model previously studied that are changed. As before, the model is going to be solved backward.

In the **third step**, as in the previous case, a lump-sum transfer is redistributed to the farmers. It now includes the AW construction costs and becomes the following one: $\widehat{LS} = \frac{\tau X - c(S)}{n}$. With such a formulation, the AW construction costs are incured by the farmers; the "polluter pays" principle is thus checked and, contrary to the benchmark case, the lump-sum transfer can either be positive or negative, according to the size of the AW.

In the **second step**, the objective function of each farmer is the same one as when the regulator does not construct an AW except that the lump-sum transfer has got a quite different value. But this has no effect on the marginal values and the solution shares the same properties as in the case where the AW is not constructed.

In the **first step**, the regulator chooses the proportional charge on pesticides, τ, that minimizes the costs needed in order to achieve the target mass, i.e. the sum of the costs of reducing the amount of pesticides used and of AW construction. We remind here that we assumed that AW construction can only be implemented by the regulator. The optimization program to be solved by the regulator is thus the following one:

$$\min_{\tau,S} n\kappa(\overline{x} - x^{\circledast}(\tau)) + c(S)$$
$$s.t. \quad : \quad \alpha X^{\circledast}(\tau) - q\left(S, \alpha X^{\circledast}(\tau)\right) = \overline{TM}$$

where $X^{\circledast}(\tau)$ shares the same properties as $X^*(\tau)$ and the superscript $\circledast$ denotes the solution of the model with AW construction.

Proposition 2 *When the regulator considers the possibility of constructing an AW in order to reduce the mass of pesticides in water, the unique solution of the model,* $\left(X^{\circledast}, S^{\circledast}, \lambda^{\circledast}, \tau^{\circledast}\right)$*, exists and is such that the marginal cost of removing one unit of pesticide from water located after the AW is the same one if an AW is constructed and if the pesticides uses are reduced, i.e. they are equal for all measures:*

$$\frac{c_S^{\circledast}}{q_S^{\circledast}} = \frac{n\kappa_\delta^{\circledast}}{\alpha\left[1 - q_M^{\circledast}\right]}$$

We now want to investigate the implications of the regulator construction of AW in order to clean up the water pollution with pesticides.

5 The implications of constructing an artificial wetland

We are going to compare the results obtained in both the versions of our model (denoted by the superscripts * and $^{\circledast}$).

First of all, if the target mass is reached in both cases, the effort made by the farmer in order to do so is quite different. Indeed, since we showed that $X^{\circledast} \in]\underline{X}, \overline{X}[$ and $S^{\circledast} \in]0, \bar{S}[$, we know from our assumptions that $q^{\circledast} > 0$. It directly follows that the amount of pesticides used by the farmers in the benchmark case is lower than the one occurring when the regulator constructs an AW, both at an individual and at an aggregate level:

$$X^{\circledast} > X^* \Leftrightarrow x^{\circledast} > x^*$$

As a consequence, AW construction reduces the aggregate, $\Delta := n\delta$, and the individual effort,

δ, that is made by the farmers of the catchment in terms of pesticides used reduction in order to reach the target mass:

$$\Delta^* > \Delta^{\circledast} \Leftrightarrow \delta^* > \delta^{\circledast}$$

What about the cost-effectiveness of reaching the target mass thanks to AW construction if some interiority assumptions (ensuring that $S \neq 0$) are relaxed? Up to this point, it seems that the construction of an AW by the regulator generates a gain, $\Gamma := n\kappa(\delta^*) - n\kappa\left(\delta^{\circledast}\right)$, which accrues to the farmers since the use of a higher amount of pesticides reduces the cost, κ, of the deviation from the point maximizing their profits, $\overline{X}$:

$$\kappa_\delta > 0 \text{ and } n\delta^* > n\delta^{\circledast} \Rightarrow n\kappa\left(\delta^*\right) > n\kappa\left(\delta^{\circledast}\right) \text{ and } \Gamma > 0$$

But in order to fully compare the cost-effectiveness of the two cases, we also have to enter into the picture the global fiscal scheme (the proportional charge, τ, but also the lump-sum transfer, LS) implemented by the regulator. As a consequence, we compare the global cost function of the farmers evaluated at the solution of each of our cases: $n\kappa(\delta^*)$ for the benchmark case and $n\kappa\left(\delta^{\circledast}\right) + c(S^{\circledast})$ for the case with AW since the fiscal schemes are respectively $(\tau^*, \widetilde{LS})$ and $(\tau^{\circledast}, \widehat{LS})$. According to the difference between the gains accruing to the farmers thanks to an AW construction and the costs induced, we can distinguish between two cases:

(i) if $\Gamma > c(S^{\circledast})$, constructing an AW in addition to a fiscal scheme is more cost-effective than not,

(ii) if $\Gamma < c(S^{\circledast})$, constructing an AW is not cost-effective.

Finally, we can simply deduce from $\kappa_{\delta\delta} > 0$ and $\kappa\left(\delta^*\right) > \kappa\left(\delta^{\circledast}\right)$ a property of the charge levied on each unit of pesticides used according to which it is higher in the benchmark case than in the case with AW construction:

$$\tau^* > \tau^{\circledast}$$

Proposition 3 *The proportional charge that has to be implemented in order to reduce pollution with pesticides to the target mass is lower than if no AW had been constructed: $\tau^* > \tau^{\circledast}$. When the AW is constructed, the total effort that is made by the farmers in order to reach the target mass in water is reduced: $\Delta^* > \Delta^{\circledast}$.*

This result can seem quite uncommon since when AW are constructed, the farmer is allowed to pollute more, i.e. this type of water pollution regulation increases the amount of pesticides used allowed. But the reader must keep in mind that the target mass is still reached. Furthermore, if we now imagine that no fiscal scheme is implemented, we know from our assumptions that the farmer will use the maximum amount of pesticides, $\overline{X}$, and that the target mass won't be reached, neither in the case without AW, nor in the one with it. Nevertheless it remains that AW allows to reduce the ambient amount of pesticides contained in water since we have:

$$\alpha\overline{X} > \alpha\overline{X} - q\left(S, \alpha\overline{X}\right) \forall S > 0$$

As a consequence, our results abet the possibility of more stringent water quality when AW can be constructed by the regulator.

6 A numerical illustration: a wine catchment area in Rouffach (North-East of France)

To illustrate the theoretical model, we further propose a numerical illustration. For this illustration, we focus on fungicide pollution from viticulture. For the ease of exposition we propose to name the assimilation of pesticides by the AW the "downstream treatment" and the abatement by the farmers the "upstream treatment".

6.1 Downstream treatment

In the framework of the LIFE Environment ARTWET project, Grégoire (Grégoire et al., 2009) and Imfeld (Imfeld et al., 2009) completed some experiments in a small catchment in Alsace (France) to simulate the credibility of an AW for removing pesticides from water.

In this catchment of 28.9 ha, about 20 kg of fungicides are applied upstream by 28 winegrowers each year, and each year about 20 g streams to the AW after rain events. The residues are assimilated or stocked upstream, and a part can be found on the groundwater in the long term. In this illustration we are only interested in the short term effect namely the fungicides that reach the AW.

In the theoretical model the treatment rises when the size S of the AW increases. Here, this effect is reproduced by increasing the size of the gravel filter. Increasing the gravel filter causes an increase of the hydraulic retention time and, therefore the removal of pesticides. Nevertheless, above a certain threshold, increasing the gravel filter more is useless.

From the observation of 12 rain events from April 2009 to July 2009, we have estimated the treatment function q according to the volume of the filter S and the mass of pesticides M as following (see appendix E for more details):

$$q(S, M) = 10^{-4}\left(-0.45S^2 + 126S\right)M$$

The functional form selected fit to the main assumptions of the theoretical model since: $q_S = 10^{-4}(-0.9S + 126)M$ and $q_M = 10^{-4}\left(-0.45S^2 + 126S\right)$. In appendix E, we also explain how we have calibrated the natural assimilative capacity (without AW) as $\alpha = 6.10^{-3}$.

The gravel filter consists in quaternary gravels from the local Alsatian quaternary floodplain and a gabion barrier in front of the filter to block the gravel mass. We used data provided by the LIFE Environment ARTWET project: the gabion barrier has a unit cost of 5000 € and the price of the gravel is about 15 € per m^3:[11]

$$C(S) = 15S + 5000$$

6.2 Upstream treatment

Leroy and Soler, within the Framework of a French project (see Bazoche et al., 2009), estimated the reduction of the mean yield when the wine-growers use less fungicides. In calibrating this information with economic data of this catchment, we estimated the following function (see appendix F for more details):

$$\kappa(\delta) = 0.0224\delta^2 + 2\delta$$

with: $\kappa_\delta = 0.0224\delta + 2$.

The abatement cost is estimated as an opportunity cost (profit loss) when the fungicides used decreases. In such a case, a part of the production is lost, because of diseases increase.

6.3 Results of the simulations

First, the reader certainly noticed that all our theoretical assumptions are not exactly checked, specially the one ensuring the uniqueness of the solution. In the simulations, we obtained a unique solution by not considering solutions with a complex part.

Without any regulation, the maximum quantity of fungicides spread upstream, $\bar{X}$, is equal to $24,620$ g.

One per 1000 reaches the AW zone, which treats again 40% of pesticides when there is no AW ($S = 0$). Then with $X = 24,620$ and $S = 0$, it remains $14,769$ mg of fungicides in the downstream of the AW.

If we want to divide this mass of pesticides by 10 without increasing S, we have to reduce X from $24,620$ g to $2,462$ g. The total abatement cost is then $436,929$ € and the charge rate is 37.4 € by gram.

[11] Let us remind that we assumed that the regulator already owns lands bordering some farmers' fields.

Nevertheless another solution would consist in a combination of upstream and downstream effort. By this way, we can reach the same target of $1,476.9$ mg with a total cost of $25,885$ € by increasing S to 139.88 (downstream cost $C(S) = 7,098$ €) and reducing X to $20,860$ g (upstream cost $K(\Delta) = 18,786$ €). The charge rate for the farmers is 8 € by gram of fungicides rejected and the difference between the charge paid and the cost of the AW construction, LS, is $159,937$ €.

Then, with the AW the percentage reduction of the total cost is 94%, and the reduction of the charge rate is about 78.5%.

A sensibility study around this target, gave us the following Figure 1 (see the detailed results with and without AW in Appendix G).

T (€) decrease	Total cost decrease	$\overline{TM}$ (mg)
92%	98%	1,700
86%	97%	1,600
80%	95%	1,500
79%	94%	1,477
74%	92%	1,400
74%	92%	1,300
68%	89%	1,200

Figure 1: Savings with AW construction

We can see on Figure 1 that the savings with the AW are very important. The magnitude of these savings seems to depend on the target.

7 Conclusion

In this paper, we proposed to consider an original method of abatement of water pollution with pesticides: AW construction. The assimilative capacity of an AW differs here from the basic natural one by the fact that it strongly depends on the size of the filter that can be adjusted by the regulator with a limited amount of land. The main difference of our paper with respect to the existing literature is that we studied the impact of considering AW construction on the fiscal scheme implemented by a regulator in order to reduce water pollution with pesticides to a target mass. We also studied its impact on the effort that is made by a farmer in order to reduce pesticides found in water bodies.

More particularly, we showed that the consideration of AW construction in order to reach a pre-determined target mass of pesticides in water can reduce both the effort that is made by the farmers and the charge on pesticides that has to be implemented. We checked this theoretical result on a numerical example. It remains true as long as the costs of constructing an AW are lower than the gains accruing to the farmers thanks to the AW construction. As a consequence, our framework is able to take into account the trade-offs that can occur between different land-usages.

Policy implications are of two natures. Firstly, our results abets the possibility for more stringent water quality standards at the national level since regulators can construct AW in order to reduce the amount of pesticides contained in water. Secondly, we know that in the real life input charges are below their optimal level for lobbying reasons. When considering the possibility of constructing an AW in addition to classic regulation tools such as environmental taxation, our results show that the input charges implemented in practice by policy-makers could come closer to the optimal input charges needed in such a situation.

Our model is so generic that it could be applied to any measure with a similar assimilative capacity and cost function. And as a consequence such a measure would result in the same conclusion with regards to efficiency of the input charge under its presence.

Nevertheless, this work contains some limits. Firstly, we need to investigate empirically the costs functions in order to lead a more robust empirical analysis and, in the line of Shibata and Winrich (1983), to see how results could be changed according to the assumptions made on this function. But in order to carry out a careful econometric analysis, we need more data related to the wine-growers production function and to the AW costs. Secondly, we did not enter into the picture the fact that AW can provide a lot of other services, in particular ecological one. Considering them induces that AW construction can even more be of major importance, assuming that these services are higher than the one induced by an input charge that would also have to be taken into account within such a framework. Indeed, the benefits induced by an input charge must include the effect on health of pesticide used reduction in agricultural production. But in the real world, the ecological services of wetlands and the effects of pesticides used reduction on health are very difficult to evaluate and, from the best of our knowledge, no economic work concentrates on the AW services. It is why we limited our work to a cost-effective framework. Finally, it would be of interest to include some dynamic effects in the assimilation process of the AW. But such an extension needs a strong help from scientists of other disciplines and it is why it is left for future works.

References

[1] Bazoche P., Cartolaro P., Deliere L., Del'Homme B., Hernandez F., Goutouly J.-P., Léger B., Leroy P., Naud O., Soler L. G., Steffe J., Ugaglia A. 2009. Vin et environnement : comment réduire les quantités de pesticides utilisés en viticulture ?, Synthèse du projet *ANR Agriculture et Développement Durable* (2005-2008)

[2] Bel F., G. Drouet d'Aubigny, A. Lacroix, A. Mollard. 2004. Efficacité et limites d'une chargee sur les engrais azotés: éléments d'analyse à partir de 16 pays européens, Economie et Prévision, 5(166), 99-113

[3] Brander L.M., R.J.G.M. Florax, J.E. Vermaat. 2006. The Empirics of Wetland Valuation: A Comprehensive Summary and a Meta-Analysis of the Literature, *Environmental and Resource Economics, 33*, 223–250

[4] Byström O. 1998. The nitrogen abatement cost in wetlands, *Ecological Economics 26*, 321-331

[5] Byström O. 2000. The replacement value of wetlands in Sweden, *Environmental and Resource Economics 16*, 347-362

[6] Byström O., H. Andersson, I.M. Gren. 2000. Economic criteria for using wetlands as nitrogen sinks under uncertainty, *Ecological Economics 35*, 35-45

[7] Crépin A.S. 2005. Incentives for wetland creation, *Journal of Environmental Economics and Management 50*, 598–616

[8] Dirksmeyer W. 2006. *Economics of Pesticide Reduction and Biological Control in Field Vegetables—A Cross Country Comparison*, Wissenschaft Verlag Vauk, Kiel KG, 246 pp.

[9] Florax R.J.G.M., C.M. Travisi, P. Nijkamp. 2005. A meta-analysis of the willingness to pay for reductions in pesticide risk exposure, *European Review of Agricultural Economics 32(4)*,441–467

[10] Grégoire C., Elsaesser D., Huguenot D., Lange J., Lebeau T., Merli A., Mose R., Passeport E., Payraudeau S., Schütz T., Schulz R., Tapia-Padilla G., Tournebize J., Trevisan M., Wanko A. 2009. Mitigation of agricultural nonpoint-source pesticides pollution in artificial wetland ecosystems, *Environmental Chemistry Letter* 7(3),.205-231

[11] Gren I.M., K. Elofsson, P. Jannke. 1997. Cost-Effective Nutrient Reductions to the Baltic Sea, *Environmental and Resource Economics* 10, 341–362

[12] Heberling M.T., J.H. García, H.W. Thurston 2010. Does encouraging the use of wetlands in water quality trading programs make economic sense?, *Ecological Economics* 69, 1988–1994

[13] Paulsen S. 2007. Investment in Wetlands for Pollution Abatement Under Uncertainty, Topics on the ecological economics of coastal zones. *Doctoral diss.* Dept. of Economics, SLU. Acta Universitatis agriculturae Sueciae

[14] Imfeld G., Braeckevelt M., Kuschk P., Richnow H. H. 2009. Monitoring and assessing processes of organic chemicals removal in constructed wetlands, *Chemosphere* 74, 349-362

[15] Shibata H., Winrich J.S. 1983. Control of pollution when the offended defend themselves, *Economica* 50, 425-437

[16] Schulz R. 2004. Field studies on exposure, effects and risk mitigation of aquatic nonpoint-source insecticide pollution—a review, *Journal of Environmental Quality 33*, 419–448

[17] Söderqvist T. 2002. Constructed wetlands as nitrogen sinks in southern Sweden: An empirical analysis of cost determinants, *Ecological Engineering 19*, 161–173

APPENDIX

A Proof of Lemma 1

(i) From equation 1, we define the following function:

$$\Psi(\tau, x) := -\kappa_\delta(\overline{x} - x) + \tau$$

We deduce from our assumptions $\lim\limits_{x\to\overline{x}} \kappa_\delta = 0$ and $\lim\limits_{x\to\underline{x}} \kappa_\delta = +\infty$ that $\lim\limits_{x\to\bar{x}} \Psi > 0$ and $\lim\limits_{x\to\underline{x}} \Psi < 0 \ \forall\tau > 0$. Furthermore, we know that $\Psi_x = \kappa_{\delta\delta} > 0$. The implicit function theorem tells us that $\exists! x \mid \Psi(\tau, x(\tau)) = 0$ and that:

$$x^*_\tau = -\frac{\Psi_\tau}{\Psi_x} = -\frac{1}{\kappa_{\delta\delta}} < 0$$

As a consequence of the fact that $X^*(\tau) := nx^*(\tau)$,

$$X^*_\tau < 0$$

(ii) If we put our assumptions $\lim\limits_{x\to\overline{x}} \kappa_\delta = 0$ and $\lim\limits_{x\to\underline{x}} \kappa_\delta = +\infty$ into equation 1, we have that $\lim\limits_{\tau\to 0} x^*(\tau) = \overline{x}$ and $\lim\limits_{\tau\to+\infty} x^*(\tau) = \underline{x}$. Finally, we have: $\lim\limits_{\tau\to 0} nx^*(\tau) = n\bar{x} = \bar{X} = \lim\limits_{\tau\to 0} X^*(\tau)$ and $\lim\limits_{\tau\to+\infty} nx^*(\tau) = n\underline{x} = \underline{X} = \lim\limits_{\tau\to+\infty} X^*(\tau)$.

B Proof of proposition 1

(i) Even if the proof of this proposition is direct and in order to clarify the section with AW, we propose here to define the solution of the problem characterizing the benchmark case as the one of an optimization program in which the regulator looks for the optimal charge minimizing the total costs incured by the farmers in order to reach the target mass $\overline{TM}$. Since we assumed that the information of the regulator is perfect and complete, it is able to anticipate the best-response of each farmer to the charge: $x^*(\tau)$. Furthermore, the lump-sum transfer and the proportional charge compensate themselves in such a way that the optimization program to be solved is the following one, where $X^*(\tau) := nx^*(\tau)$:

$$\min_{\tau} n\kappa(\overline{x} - x^*(\tau))$$
$$s.t. \quad : \quad \alpha X^*(\tau) = \overline{TM}$$

We then construct the following Lagrangian equation:

$$\Lambda(\tau, \lambda) = n\kappa(\overline{x} - x^*(\tau)) + \lambda\left[\alpha X^*(\tau) - \overline{TM}\right]$$

We know from the (i) of lemma 1 and $\alpha\overline{X} > \overline{TM} > \alpha\underline{X}$ that the constraint qualification is checked since $\exists\tau \mid \begin{Bmatrix} \alpha X^*_\tau < 0 \\ \alpha X^*(\tau) = \overline{TM} \end{Bmatrix}$.

If τ^* is a solution of the regulator problem then there exists a unique λ^* such that the following first order conditions are satisfied:

$$X^*_\tau\left[-n\kappa^*_\delta + \alpha\lambda^*\right] = 0 \tag{2}$$

$$\alpha X^* - \overline{TM} = 0 \tag{3}$$

The convexity of the Lagrangian equation is checked thanks to the (i) of Lemma 1: $(-n\kappa_\delta X_\tau + \lambda^* \alpha X_\tau)_\tau = n\kappa_{\delta\delta} X_\tau^2 - n\kappa_\delta X_{\tau\tau} + \lambda^* \alpha X_{\tau\tau} = n\kappa_{\delta\delta} X_\tau^2$. So, (τ^*, λ^*) is a global minimum.

Our assumptions on the target mass, $\alpha\overline{X} > \overline{TM} > \alpha\underline{X}$, insure that $X^*(\tau) \in]\underline{X}, \overline{X}[$ and the interiority of the charge rate, i.e. $\tau^* \in]+\infty, 0[$, then directly comes from (ii) of lemma 1. It follows that $\lambda^* > 0$.

It then directly follows that:

$$(3) \quad \Leftrightarrow \quad X^* = \frac{\overline{TM}}{\alpha}$$
$$(2) \quad \Leftrightarrow \quad \lambda^* = \frac{n\kappa_\delta^*}{\alpha}$$

(ii)

$$\begin{Bmatrix} X_\alpha^* = -\frac{\overline{TM}}{\alpha^2} < 0 \\ X_{\overline{TM}}^* = \frac{1}{\alpha} > 0 \end{Bmatrix}$$

(iii)

$$\begin{Bmatrix} \tau_\alpha^* = -\kappa_{\delta_i\delta_i}^* X_\alpha^* > 0 \\ \tau_{\overline{TM}}^* = -\kappa_{\delta_i\delta_i}^* X_{\overline{TM}}^* < 0 \end{Bmatrix}$$

C Proof of proposition 2

In order to define the solution of this problem, we construct the following Lagrangian equation, where $X^\circledast(\tau) := nx^\circledast(\tau)$:

$$L(\tau, S, \lambda) = n\kappa(\overline{x} - x^\circledast(\tau)) + c(S) + \lambda\left[\alpha X^\circledast(\tau) - q\left(S, \alpha X^\circledast(\tau)\right) - \overline{TM}\right]$$

The constraint qualification is checked since we know from the (i) of lemma 1, and the assumptions $1 > q_M > 0$, $q_S > 0$ and $\alpha\overline{X} - q(S, \alpha\overline{X}) > \overline{TM} > \alpha\underline{X}$ $\forall S$ that $\exists \tau, S \mid \begin{Bmatrix} \alpha X_\tau^\circledast \left[1 - q_M^\circledast\right] < 0 \\ \alpha X^\circledast(\tau) - q\left(S, \alpha X^\circledast(\tau)\right) = \overline{TM} \\ -q_S^\circledast < 0 \end{Bmatrix}$

If $(\tau^\circledast, S^\circledast)$ is a solution of the regulator problem then there exists a unique $\lambda^\circledast$ such that the following first order conditions are satisfied:

$$X_\tau^\circledast \left[-n\kappa_\delta^\circledast + \alpha\lambda^\circledast\left(1 - q_M^\circledast\right)\right] = 0 \tag{4}$$

$$c_S^\circledast - \lambda^\circledast q_S^\circledast = 0 \tag{5}$$

$$\alpha X^\circledast - q\left(S^\circledast, \alpha X^\circledast\right) - \overline{TM} = 0 \tag{6}$$

Let H denotes the Hessian matrix of $L(\tau, S, \lambda^\circledast)$:

$$H = \begin{bmatrix} X_\tau\left(n\kappa_{\delta\delta}X_\tau - \alpha\lambda^\circledast q_{MM}X_\tau\right) + X_{\tau\tau}\left(-n\kappa_\delta + \alpha\lambda^\circledast(1 - q_M)\right) & -\alpha\lambda q_{SX} \\ -\alpha\lambda q_{XS} & c_{SS} - \lambda^\circledast q_{SS} \end{bmatrix}$$

We deduce from the evaluation of this matrix at the optimum that the minimum defined by the previous first order conditions is a local one, since:

$$H^\circledast = \begin{bmatrix} n\kappa_{\delta\delta}^\circledast X_\tau^{\circledast 2} & 0 \\ 0 & 0 \end{bmatrix} > 0$$

Our assumptions on the target mass,$\alpha\overline{X} - q(S, \alpha\overline{X}) > \overline{TM} > \alpha\underline{X}$ $\forall S$, insure that $X^\circledast(\tau) \in]\underline{X}, \overline{X}[$ and the interiority of the charge rate, i.e. $\tau^\circledast \in]+\infty, 0[$, then directly comes from (ii) of Lemma 1. It follows that $\lambda^\circledast > 0$. Putting now the assumptions $\lim_{S\to 0} q_S > 0$ $\forall X > 0$ and $\lim_{S\to 0} c_S = 0$ along with $\lim_{S\to\overline{S}} q_S = 0$ $\forall X > 0$ and

$\lim_{S \to \bar{S}} c_S = +\infty$ in the first order equation related to S we have that $S \in]0, \bar{S}[$.

It then directly follows that:

$$\begin{aligned}
(6) \quad &\Leftrightarrow \quad \overline{TM} = \alpha X^{\circledast}(\tau) - q^{\circledast} \\
(4) \quad &\Leftrightarrow \quad \lambda^{\circledast} = \frac{n\kappa_{\delta}^{\circledast}}{\alpha\left[1 - q_M^{\circledast}\right]} > 0 \\
(5) \quad &\Leftrightarrow \quad c_S^{\circledast} = \lambda^{\circledast} q_S^{\circledast}
\end{aligned}$$

D Proof of proposition 3

The elements of the proof are given in the text.

E Calibration of the pesticides assimilative capacity of the AW

At the entrance to the public land (where the AW is constructed), it remains only 1/1000 of the quantity X of fungicides rejected upstream. Without AW construction ($S = 0$), the soil could treat another 40% of fungicides. Then we have: $\alpha = 6/10,000$.

On average, we know from soils experts involved in the LIFE Environment ARTWET project previously quoted that the Rouffach AW treatment increases from 40% to 80% with $S = 67.2\ m^3$, and to 90% with $S = 134.4\ m^3$

Then, by extrapolation, we look for a function that crosses these points, and with a derivative equal to zero for $\bar{S} = 140\ m^3$. We obtain:

$$\frac{q}{X} = 10^{-7}\left[-0.27S^2 + 75.6S\right]$$

and:

$$q(S, M) = 10^{-4}\left[-0.45S^2 + 126S\right] M$$

since $M := \alpha X$.

F Calibration of the pollution abatement cost

The following Figure 2 is obtained thanks to the Leroy and Soler results (Bazoche et al., 2009).

Yields (100kg/ha)	Number of fungicides applications
99%	8
92.5%	6
82.5%	4
37.5%	0

Figure 2: Yields according to the number of fungicides applications

In the studied catchment, about 20 kg of fungicides are spread upstream each year by the 28 wine-growers who are assumed identical. As a consequence, 0.714 g of fungicides are spread by each wine-grower The vineyard average yield was 95% in 2008[12], which corresponds, on average, to 6.5 applications of fungicides. So we suppose that the whole wine-growers use $3,077$ g of fungicides by application.

In the Upper-Rhine French administrative department, the viticulture sales are, on average, $293,000,000$ € on $9,000$ ha[13]. Then, we estimate that in the 28.9 ha (namely a little more than 1 ha per wine-grower) of our studied catchment, the sales are $940,856$ € (namely $33,602$ € per wine-grower).

Therefore, we estimate that a yield equal to 95% corresponds to sales equal to $940,856$ €. To find the wine-grower profit, we deduct the costs from the sales. First, the fungicides costs are estimated at $1,334$ € by application in the whole catchment (namely $47,6$ € per wine-grower). The other costs represent, on average, 56% of the sales: 85% are fixed and 15% are proportional to the yield.

We consider that the total upstream treatment cost is the difference between the profit with a maximum yield (obtained with a maximal quantity of fungicides: $24,615$ g namely 879 g per wine-grower), and the profit with the quantity of fungicides actually used.

Figure 3 sums up the simulations run on these basis.

Yield	Number of applications	Fungicides quantity	Sales	Fungicides costs	Other costs	Profit	Treatment	Upstream treatment cost
38%	0	0	370,931	0	479,005	-108,075	24,615	539,754
45%	0.5	1,538	439,907	667	484,799	-45,559	23,077	477,238
51%	1	3,077	504,694	1,334	490,242	13,119	21,538	418,560
57%	1.5	4,615	565,292	2,001	495,332	67,959	20,000	363,720
63%	2	6,154	621,701	2,668	500,070	118,962	18,462	312,717
68%	2.5	7,692	673,920	3,335	504,456	166,128	16,923	265,551
73%	3	9,231	721,949	4,002	508,491	209,456	15,385	222,223
78%	3.5	10,769	765,790	4,669	512,174	248,947	13,846	182,732
82%	4	12,308	805,441	5,336	515,504	284,600	12,308	147,079
85%	4.5	13,846	840,902	6,003	518,483	316,416	10,769	115,263
88%	5	15,385	872,175	6,670	521,110	344,395	9,231	87,284
91%	5.5	16,923	899,258	7,337	523,385	368,536	7,692	63,143
94%	6	18,462	922,151	8,004	525,308	388,839	6,154	42,840
95%	6.5	20,000	940,856	8,671	526,879	405,305	4,615	26,374
97%	7	21,538	955,370	9,338	528,098	417,934	3,077	13,745
98%	7.5	23,077	965,696	10,005	528,966	426,725	1,538	4,954
99%	8	24,615	971,832	10,672	529,481	431,679	0	0

Figure 3: Upstream data for the whole catchment

In accordance with the Figure 4, we choose the function:

$$K(\Delta) = 0.0008\Delta^2 + 2\Delta$$

We then deduce the individual cost function from:

$28\kappa(\delta) = K(28\delta)$

$\Leftrightarrow 28\left(\beta_1\delta^2 + \beta_2\delta\right) = 0.0008(28\delta)^2 + 2(28\delta)$

$\Leftrightarrow \beta_1 = 0.0224$ and $\beta_2 = 2$

Thus, the individual cost function is the following one:

[12] Source: "Agreste" national data 2008

[13] Source: http://www.haut-rhin.chambagri.fr/AGRI68/FILIERES/filiere_viticole.PDF

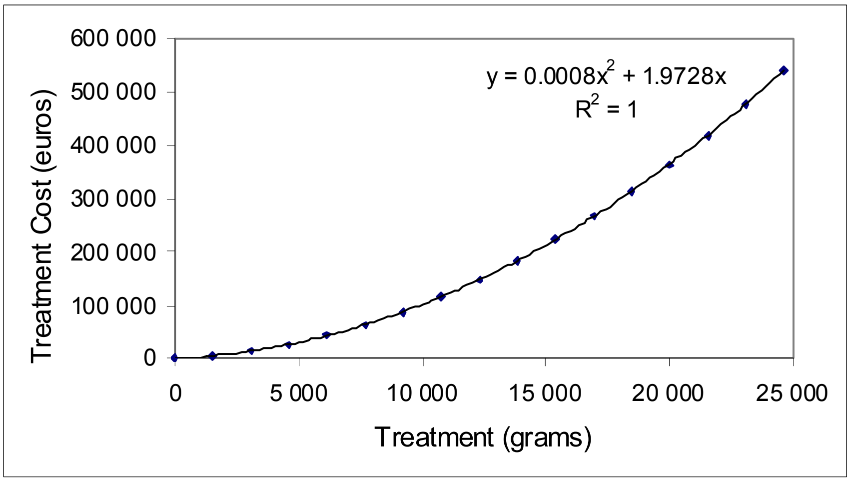

Figure 4: Upstream treatment cost function

$$\kappa(\delta) = 0.0224\delta^2 + 2\delta$$

G Sensibility study

Without Wetland Restoration						
X (g)	S (m3)	T (€)	K (€)	C (€)	Total cost	$\overline{TM}$ (mg)
2,833	0	36.9	423,116	0	**423,116**	1,700
2,667	0	37.1	429,280	0	**429,280**	1,600
2,500	0	37.4	435,489	0	**435,489**	1,500
2,462	0	37.4	436,929	0	**436,929**	1,477
2,333	0	37.7	441,741	0	**441,741**	1,400
2,167	0	37.9	448,039	0	**448,039**	1,300
2,000	0	38.2	454,381	0	**454,381**	1,200

Figure 5: Sensibility study without AW construction

Optimum							
X (g)	S (m3)	T (€)	LS (€)	K (€)	C (€)	Total cost	$\overline{\mathrm{TM}}$ (mg)
24,010	139.72	3	64,162	1,503	7,096	**8,598**	1,700
22,599	139.83	5	111,007	7,285	7,098	**14,383**	1,600
21,186	139.88	7	151,500	16,262	7,098	**23,360**	1,500
20,860	139.88	8	159,937	18,786	7,098	**25,885**	1,477
19,769	139.90	10	185,713	28,476	7,098	**35,574**	1,400
18,359	139.91	12	213,380	43,818	7,099	**50,917**	1,300
16,952	139.92	14	234,656	62,309	7,099	**69,408**	1,200

Figure 6: Sensibility study with AW construction