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Is it worth protecting groundwater from diffuse pollution with agri-environmental schemes? A hydro-economic modeling approach

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ABSTRACT

In Europe, 30% of groundwater bodies are considered to be at risk of not achieving the Water Framework Directive (WFD) 'good status' objective by 2015, and 45% are in doubt of doing so. Diffuse agricultural pollution is one of the main pressures affecting groundwater bodies. To tackle this problem, the WFD requires Member States to design and implement cost-effective programs of measures to achieve the 'good status' objective by 2027 at the latest. Hitherto, action plans have mainly consisted of promoting the adoption of Agri-Environmental Schemes (AES). This raises a number of questions concerning the effectiveness of such schemes for improving groundwater status, and the economic implications of their implementation. We propose a hydro-economic model that combines a hydrogeological model to simulate groundwater quality evolution with agronomic and economic components to assess the expected costs, effectiveness, and benefits of AES implementation. This hydro-economic model can be used to identify cost-effective AES combinations at groundwater-body scale and to show the benefits to be expected from the resulting improvement in groundwater quality. The model is applied here to a rural area encompassing the Hesbaye aquifer, a large chalk aquifer which supplies about 230,000 inhabitants in the city of Liege (Belgium) and is severely contaminated by agricultural nitrates. We show that the time frame within which improvements in the Hesbaye groundwater quality can be expected may be much longer than that required by the WFD. Current WFD programs based on AES may be inappropriate for achieving the 'good status' objective in the most productive agricultural areas, in particular because these schemes are insufficiently attractive. Achieving 'good status' by 2027 would demand a substantial change in the design of AES, involving costs that may not be offset by benefits in the case of chalk aquifers with long renewal times.

1. Introduction

All the water quality surveys conducted during the last ten years have clearly shown that European groundwater bodies are severely affected by diffuse agricultural pollution (Collins and McGonigle, 2008; Visser et al., 2009). This type of pollution is one of the main pressures affecting groundwater bodies. This situation is not new and significant efforts have been made in the agricultural sector since the early 1990s to reverse the trend, following the publication of the Nitrate Directive (91/676/EC). Farmers working in Nitrate Vulnerable Zones are required to adhere to a program of mandatory and uncompensated measures aimed at reducing the amounts of nitrate leaching from their lands and polluting the groundwater.

The situation changed with the publication of the Water Framework Directive or WFD (2000/60/EC) in 2000. Member States now have a legal obligation to restore all groundwater bodies to a good chemical status. Nitrate concentrations in groundwater should not exceed drinking-water standards, i.e., 50 mg/l. The Directive also requires Member States to identify and reverse any significant upward trend in pollutant concentrations. Achieving

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Abbreviations: AEP, agri-environmental payment; AEP*, agri-environmental payment required to reach the target effectiveness E*; AES, agri-environmental scheme; AFI, agri-environmental footprint index; B, benefits; C, cost for the society; CAP, common agricultural policy; C^R, cost for the regulator; D, damage costs; D^C, damage costs resulting from averting behaviour of tap water consumers; D^P, damage costs resulting from avoidance actions taken by tap water producers; E, effectiveness; E*, target effectiveness; EBI, environmental benefits index; Ha, hectare; NB, net benefits; NLOSS, mean annual nitrate leaching; NO_3, nitrate concentration in groundwater; NO_3^A, nitrate concentration at groundwater-withdrawal points; NO_3^R, nitrate concentration at representative quality-monitoring points; S, implementation area; WFD, water framework Directive.

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this objective by 2015 (with a possible extension until 2027) is a real challenge for many Member States, since 30% of groundwater bodies are currently considered to be at risk of not achieving the 'good status' objective by 2015, and 45% are in doubt of doing so (EC, 2007).

For groundwater bodies at risk, Member States must design cost-effective programs of measures. The action plans developed to meet this requirement mainly consist of promoting the adoption of agri-environmental schemes (AES). These were first introduced into the European Common Agricultural Policy (CAP) during the late 1980s as an option to be applied by Member States, and have been particularly encouraged since the 1999 CAP reform by European Regulation EC/1698/99, which sets out their objectives and the principles of compensation. Under these schemes, farmers agreeing to change their cropping practices beyond the standard of Good Agricultural Practice for a minimum period of five years receive financial compensation, the level of which is intended to compensate for income losses, by application of the 'Provider Gets' principle (Hanley et al., 1999). Meeting the WFD objectives through changes in agricultural practices means targeting the implementation of these schemes in the areas at risk, and ensuring that a sufficient number of farmers sign on to them. However, the sign-up rate might in some cases be too low to be truly effective, especially in the most productive agricultural areas, which are often major sources of pollution and where the financial compensation offered may not compensate for the real losses of income. This raises several questions:

- Are AES an appropriate means for restoring groundwater affected by diffuse pollution to 'good status'?
- What would be the total budget required?
- Are the costs of restoring good chemical status covered by the benefits? If not, should Member States take the political decision not to comply with the WFD, arguing that the costs are disproportionate as defined in Article 4 of the WFD?

This paper presents an attempt to answer these questions by developing and applying an innovative framework for AES evaluation in the context of diffuse agricultural pollution of groundwater. Various approaches have been used since the 1990s to evaluate the environmental effects of AES. Various types of impact model have been used, ranging from quantitative to 'common sense' models (Primdhal et al., 2010). Measurements and evaluations of the environmental effects of AES based directly on environmental outcomes generally involve serious difficulties (Primdahl et al., 2003). Evaluations of AES effects are therefore mostly based on the assessment of farmer sign-up rates and area participation (Hanley et al., 1999) and on the impacts of AES on agricultural practices ('performance' effect quoted by Primdahl et al., 2003). Criteria for evaluating effectiveness have been proposed in order to assess the impact of AES on specific environmental outcomes, such as target plant species as indicators of biodiversity, as used by Haaren and Bathke (2008), and the Agri-Environmental Footprint (AFI) index proposed by Purvis et al. (2009), which considers impacts on a wide range of environmental outcomes such as natural resources, biodiversity, and landscape. Zhang et al. (2012) use the FARMSCOPER tool for assessing the effects of mitigation methods for diffuse agricultural pollution in terms of decreases in the emissions of certain pollutants. Efficiency evaluation criteria incorporating economic components have also been developed, e.g., the US Environmental Benefits Index (EBI), which includes indicators of environmental outcomes together with the costs and on-farm benefits of implementing agri-environmental policies (Claassen et al., 2008), and the UK Cost-Benefit Analysis of AES based on the contingent valuation method (Hanley et al., 1999).

However, most of these criteria assess AES environmental outcomes in terms of a decrease in the pressures exerted on the environment, not as a change in the environmental status itself. They also rarely consider the time lag between AES implementation and the change in environmental status, or between the costs and benefits of AES. Accordingly, their design is unsuitable for evaluating AES in terms of their ability to improve groundwater quality so as to develop cost-effective programs for achieving WFD objectives. Grønvald et al. (2008) proposed an interesting framework for assessing cost-effectiveness, including the wider impacts of various measures for groundwater protection. However, they focused on a comparison between measures, without explicitly considering the impacts on groundwater quality and the benefits expected from an improvement in groundwater quality.

We propose to use hydro-economic modeling at groundwater-body scale to evaluate AES. Hitherto, a number of studies have proposed modeling approaches incorporating both economics and hydrogeology and dealing with diffuse pollution at groundwater-body scale[1] (e.g., Almasri and Kaluarachchi, 2005; Graveline and Rinaudo, 2007; Graveline et al., 2007; Ledoux et al., 2007; Peña-Haro et al., 2009, 2010; Viavattene, 2006). However, the complete economic analysis required by the WFD is generally not provided by these models, which are as yet rarely applied in real-life water management (Heinz et al., 2007).

This paper describes the development of a hydro-economic model which simulates the cost, effectiveness, and benefits associated with various AES combinations at groundwater-body scale. The model can be used to design cost-effective AES combinations as a function of the year in which 'good' groundwater status can be achieved, and to compare these combinations through a cost-benefit analysis. It is applied here to the catchment encompassing the Hesbaye aquifer in Belgium.

2. Study area

The Hesbaye aquifer is located in the Meuse River Basin, in the eastern part of Belgium, northwest of Liege (Fig. 1). The aquifer is characterized by a chalk layer 20–50 m thick underlying 2–20 m of eolian loess deposits. This important groundwater resource is affected by diffuse agricultural pollution. The catchment has been defined as a Nitrate Vulnerable Zone following the transposition of the Nitrate Directive (91/676/EEC) into the Walloon law in 2002. At present, the mean nitrate concentration in the groundwater is close to the 50 mg/l limit for drinking water set by the Drinking Water Directive (98/83/EC). Estimated groundwater quality trends indicate that mean nitrate concentrations in the water body will exceed the drinking water limit within a few years (Batlle-Aguilar, 2007; Visser et al., 2009). Consequently, the Hesbaye groundwater body has been identified by the Walloon Region as being at risk of not reaching 'good' water status by 2015.

The catchment overlaying the unconfined part of the aquifer (480 km^2) is mainly covered by agricultural lands that are the main source of nitrate fluxes into groundwater, followed by domestic wastewater discharges (Dautrebande and Soheir, 2004). Owing to its flat topography and its fertile loess deposits, this catchment is one of the most productive agricultural areas in the Walloon Region, with farms mainly specializing in cereals (wheat, barley, and maize) and industrial crops (sugar beet, potatoes, chicory, and flax) covering more than 80% of the agricultural area. Crop yields are among the highest in the Region: the average standard gross

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[1] The literature is much more abundant for hydro-economic models dealing with quantitative management or surface water management issues (for reviews, see Brouwer and Hofkes, 2008; Heinz et al., 2007).

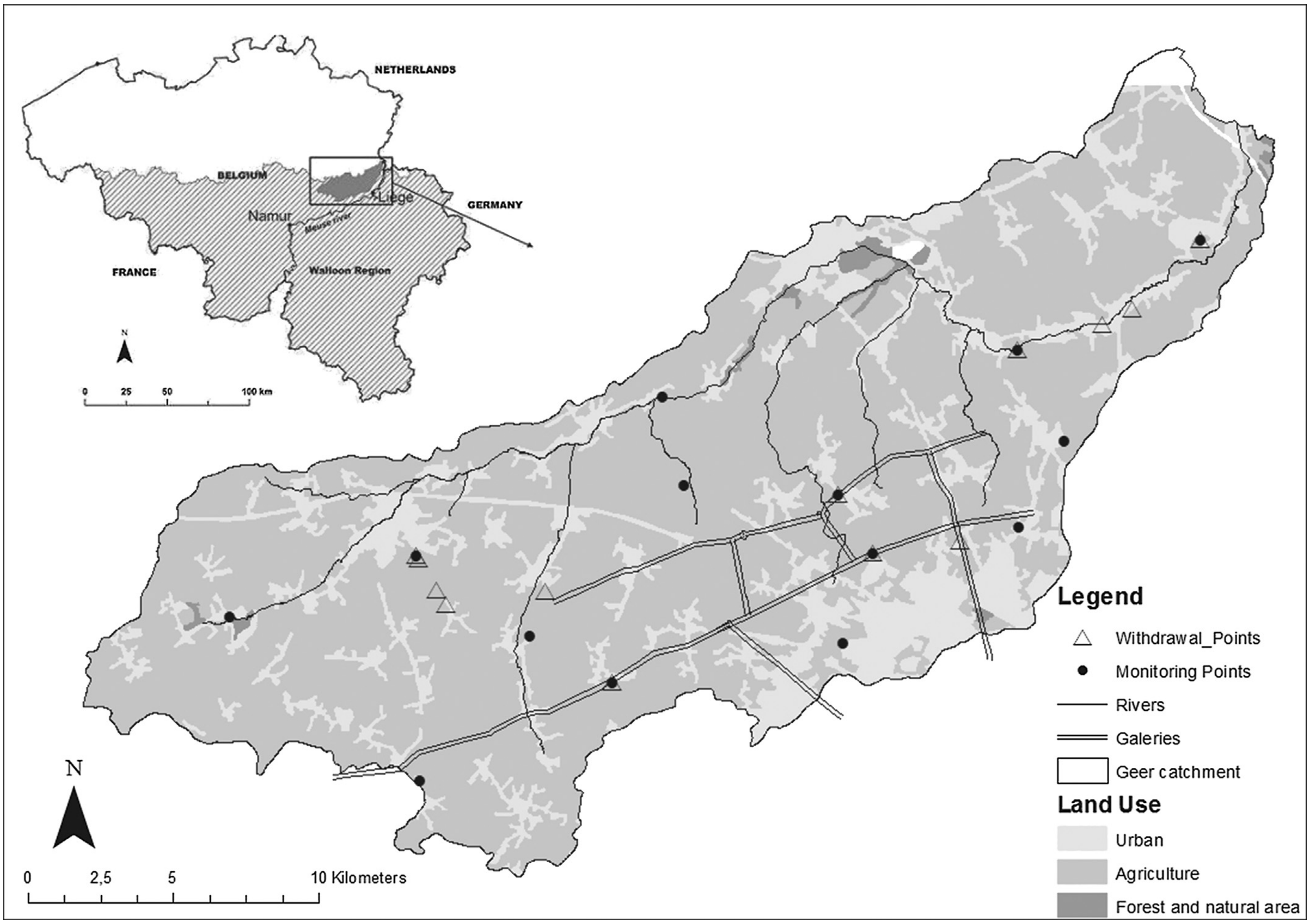

Fig. 1. Study area location.

margin over the 2005–2009 period across the catchment area is 1684 euros per hectare per year, i.e., 175 percent of the average for the Walloon Region.

In this context, designing a cost-effective program of measures may encounter difficulties related to the low economic attractiveness demonstrated by existing AES and the resulting reluctance of many farmers to change their current practices. The average budget provision in the Walloon Rural Development Plan for the Hesbaye catchment area is estimated at 0.8 million euros per year for the 2007–2013 period. Eleven AES were proposed in the 2007–2013 Walloon Rural Development Plan but many of these are not relevant to the study area either because they do not concern agriculture specializing in cereals and industrial crops, or because they are expected to have limited effects on groundwater quality. Three of them: conversion to organic farming, implementation of catch crops, and introduction of extensive cereal crops – and an additional AES which is particularly relevant to the study area (conversion of arable land into grassland) – are analyzed in this paper (see details in 4.2). Reversing the nitrate trends in groundwater and achieving good groundwater status would potentially require large-scale implementation of these measures.

The Hesbaye aquifer is also one of the most exploited groundwater bodies in the Walloon Region, with about 20 million cubic meters withdrawn each year. Estimated groundwater quality trends show that if no groundwater-protection measures are taken, the costs of environmental damage will rise during the coming years and may have to be borne directly by the economic sectors that depend on this groundwater resource. The main water user is the public water sector (87%), followed by the industrial sector (12%, mainly for cooling), and then agriculture and services (1%). The public water sector is particularly concerned since adaptive strategies will have to be implemented if nitrates exceed the admissible 50 mg/l concentration for drinking water, especially as no sustainable alternative resource has so far been identified for Liège's public water supply.

3. Methodology

We propose a hydro-economic model which combines a hydrogeological model to simulate changes in groundwater quality with agronomic and economic components to assess the costs, effectiveness, and benefits expected from the implementation of AES. The hydro-economic model comprises four modules, which are described below (Fig. 2) together with the way in which they may be combined to implement cost-effectiveness analysis and cost-benefit analysis.

3.1. Agro-economic module M1

M1 simulates the farmers' decisions to adopt AES or not, taking into account potential technical and economic constraints. This module consists of a series of Excel spreadsheets containing the agricultural land-use distribution (Table 1), existing crop rotations over the groundwater-body's catchment area (Table 2), technical

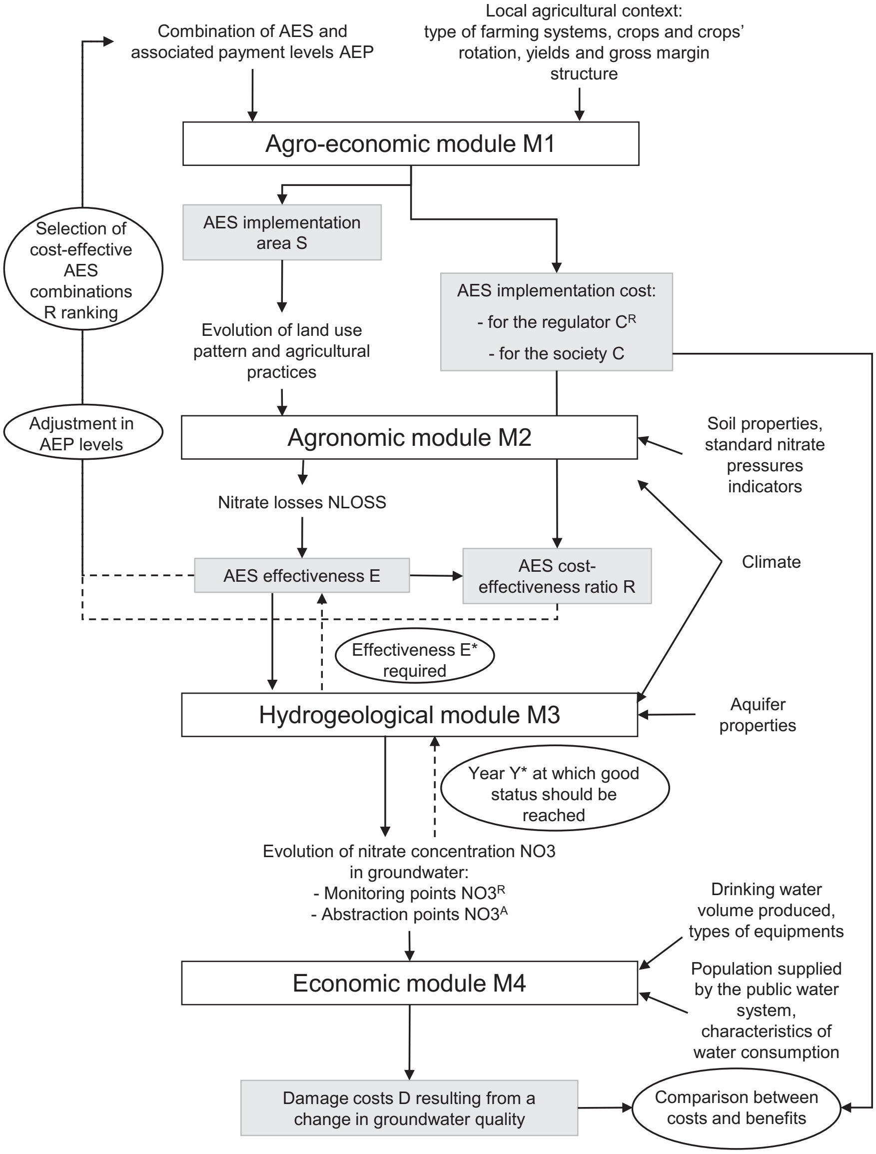

Fig. 2. Schematic describing the hydro-economic modeling framework.

descriptions of current farming practices, details of gross margins per crop, and the economic impacts (e.g., yield losses, increased production costs) resulting from AES implementation. For a given AES, the M1 module delivers two key outputs: the AES implementation area S (ha) and cost C (€/year).

M1 defines the AES implementation area S as the agricultural area where the measure can technically be implemented, taking into account the economic attractiveness of the measure and the farmers' willingness to participate. A major characteristic of AES is that their implementation is based on voluntary participation by farmers (as opposed to mandatory measures): implementation of the scheme is therefore strongly dependent on the level of agri-environmental payment level. We consider here that an AES is attractive when its payment level is high enough to fully cover the real cost borne by the farmer in implementing the scheme. The underlying assumption is that farmers aim to maximize their gross margins. A farmer's willingness to participate is also expected to be limited by a potential lack of information about the scheme, a perception that agricultural pollution in the area is low, and an aversion to changes in farming practice (Haaren and Bathke, 2008; Toma and Mathijs, 2007). We assume here that 70% of farmers may implement an AES that is technically feasible and sufficiently attractive.

The economic cost of implementing an AES can be expressed in two different ways: from the regulator's point of view or from society's point of view.

- The cost for the regulator (C^R) is a direct function of the payment level and the area of AES implementation. This cost is an important indicator for a regulator with budget constraints, since it represents the amount the regulator will effectively spend to implement the programs. This can be divided into two components: direct costs and transfer costs. Direct costs result from the implementation of the measure by a farmer in comparison with the practices he would otherwise have applied (e.g., yield losses, increased production costs). These costs are considered to be fully or even over-compensated by the payment provided by the regulator (Walloon Region and European Union) as this is the necessary condition for the measure to be attractive. In the case of overcompensation, transfer costs arise

Table 1
Land use, mean annual nitrate leaching (NLOSS) and gross margin per crop.

Crop	Area[a] ha	NLOSS[b] mg/l	Gross margin[c] €/ha/year
Wheat (winter)	9266	55	1301
Wheat (spring)	55	35	939
Barley (Winter)	1282	55	1200
Barley (spring)	136	35	908
Silage maize	863	125	858
Grain maize	67	85	1166
Sugar beet	4800	55	1880
Potatoes	766	120	2784
Permanent grass	3473	25	606
Temporary grass	360	25	900
Pulses	929	140	1218
Chicory	1047	85	1633
Flax	2213	120	1220
Rape	115	80	782
Vegetables	396	140	17,468
Fruits	366	140	10,763
Other	1367	55	1222
Total	27,501	67	1684

[a] 2005 land use data provided by the University of Liège.
[b] NLOSS estimated from AERM (2005), Ramon and Benoit (1998), Vandenberghe and Marcoen (2004).
[c] 2005–2009 mean gross margins from the Belgian agricultural statistics.

(Claassen et al., 2008; Hanley et al., 1999). These represent a gain for the farmer and a cost for the taxpayer: when considering the society as a whole they cancel each other out.

- The cost for the society (C) is the sum of direct costs and transaction costs. This cost is used to select the most cost-effective AES program[2] and to compare the costs and benefits of improving groundwater quality. Transaction costs include administrative costs for the regulator (e.g., cost of formulating the program, selecting participants, entering into contracts, making payments) and for the farmers (e.g., cost of subscribing to an AES). While transaction costs for EU agri-environmental programs are not easily available (Baylis et al., 2008), Falconer and Whitby (1999) provide an analysis of transaction and administrative costs across eight Member States. Their estimates of the average ratio of transaction costs to direct costs for Belgium (63%) is used in this paper.

M1 produces new agricultural land-use patterns resulting from the implementation of an AES or a combination of AES. These patterns are characterized by the distribution of the area Ai of each crop i. They are used as an input for the M2 module.

3.2. Agronomic module M2

The agronomic module estimates mean annual nitrate leaching beneath the root zone, expressed in mg/l. For a given type of crop i, mean annual nitrate leaching $\mathrm{NLOSS_i}$ is estimated by a simplified approach based on standard nitrate concentrations in leaching water per crop (Table 1) adapted from the results of French case studies (AERM, 2005; Ramon and Benoit, 1998) together with results from the Walloon Region found in Vanderberghe and Marcoen (2004). The mean nitrate leaching at the groundwater-body scale NLOSS is obtained by aggregating these standard concentrations, with A_i being the area of crop i in the study area.

$$\mathrm{NLOSS} = \sum A_i.\mathrm{NLOSS}/\sum A_i$$

Table 2
Area per type of crop rotation.

Crop rotation	ha	%
Sugar beet – wheat – barley – chicory – wheat	5235	19
Sugar beet – wheat – barley – flax – wheat	1483	5
Sugar beet – wheat – potatoes – wheat	3062	11
Sugar beet – wheat – maize – wheat	3720	14
Sugar beet – flax – wheat	5528	20
Temporary grass – temporary grass – wheat	539	2
Sugar beet – wheat – rape – wheat	345	1
Sugar beet – wheat – wheat	300	1
Pulses – wheat	1515	6
Fruits & vegetables	762	3
Permanent grass	3473	13
Other	1539	6
Total	27,501	100

This module is used to assess the change in NLOSS resulting from the implementation of an AES or of a combination of AES. The effectiveness E (%) of an AES is assessed by coupling M1 and M2; it is the percentage difference between the mean annual nitrate leaching into the groundwater body in a situation with AES ($\mathrm{NLOSS_{AES}}$) and a baseline situation without AES ($\mathrm{NLOSS_{baseline}}$).

$$E = 100 \times (\mathrm{NLOSS_{baseline}} - \mathrm{NLOSS_{AES}})/\mathrm{NLOSS_{baseline}}$$

The cost-effectiveness ratio R of an AES can be estimated by dividing the cost C (€/year) by the effectiveness E. R can be interpreted as the annual cost necessary to decrease overall nitrate pressure on the groundwater body by 1% through implementing the AES.

$$R = C/E$$

3.3. Hydrogeological module M3

The hydrogeological module M3 is a 3-D spatially-distributed calibrated groundwater-flow and solute-transport model which simulates nitrate transfer from the root zone into the groundwater across the partially saturated zone, and then throughout the groundwater. It was developed using the SUFT3D (Saturated – Unsaturated Flow and Transport in 3-D) finite element code (Brouyère, 2001; Brouyère et al., 2004; Carabin and Dassargues, 1999). The various solute transport processes considered in this code include advection, hydrodynamic dispersion, linear degradation, equilibrium sorption, and a physical non-equilibrium first-order dual-porosity model. To handle the problem of solute transport modeling at regional scale (i.e., parameterization of poorly characterized media and long computational time or numerical instabilities), this code was adapted to take into account the specificities of regional modeling of groundwater flow and solute transport (Brouyère et al., 2009; Orban et al., 2010). Further details concerning the modeling theories, manipulations, data employed and sensitivity analysis for the main parameters are presented in Orban (2009) and Orban et al. (2010).

This module is used to compute the NO3 nitrate concentrations in groundwater over a fifty-year period (2010–2060) that result from changes in the mean annual nitrate leaching from agriculture (NLOSS) provided by M2. Results are available for 14 representative quality-monitoring points ($\mathrm{NO_3^R}$) and 15 groundwater-withdrawal points ($\mathrm{NO_3^A}$).

3.4. Economic module M4

Several categories of damage may be caused by groundwater contamination: these damage may be related to direct use

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[2] The Baumol and Oates (1988) definition of cost-effectiveness has been used here: 'achieving an environmental goal at the lowest possible cost to the society'.

(e.g., drinking water supply, irrigation), indirect use (e.g., ecosystem in connected surface water), or non-use values (e.g., bequest, altruism, and existence values). M4 uses the avoidance-costs method (Abdalla, 1994; Rinaudo et al., 2005) to simulate the benefits expected for drinking water users from groundwater protection. Since it considers only direct-use values, M4 thus provides lower-bound estimates of the benefits.

The avoidance-cost method considers that deterioration in groundwater quality creates avoidance costs for tap water producers and averting expenditures for the tap water consumers supplied by this resource. Two types of damage are thus simulated by M4 as a function of changes in the groundwater nitrate concentration NO_3^A at each withdrawal point simulated by M3: the avoidance actions taken by tap-water producers and the averting behaviors adopted by public-water consumers (Fig. 3). The data were gathered with the help of the experts in the drinking-water sector whom we consulted and from a review of local technical literature.

- Tap-water producers should take avoidance actions if nitrate concentrations at groundwater withdrawal points exceed 50 mg/l (Drinking Water Directive), in order to keep public-water quality in line with drinking-water standards. These may consist of well closure, well displacement, water treatment, or a switch to other water resources. Damage costs (D^P) resulting from these avoidance actions will be borne by tap-water consumers through an increase in their water bills.
- At the household level, the avoidance-cost method infers damage by measuring the consumption of goods or services that substitute for the environmental quality change (Abdalla, 1994). The underlying assumption is that people make choices in order to maximize their level of well-being when faced with the increased health risks associated with exposure to unsafe drinking water (Whitehead et al., 1998). Tap-water consumers may increase their consumption of bottled water to replace tap water because of a deterioration in groundwater quality. Although nitrate concentrations in distributed water may not exceed the 50 mg/l limit (according to the requirements of the Drinking Water Directive) and bottled water costs 160 times more than tap water, this behavior may be explained by the fact that consumers generally prefer naturally clean water to water that has been polluted and treated (Hasler et al., 2005). Damage costs (D^C) resulting from this averting behavior are directly borne by tap-water consumers.

We have considered that these avoided actions and averting behaviors are adopted shortly before the drinking water limit is reached, when the nitrate concentration exceeds the 48 mg/l defined here as the ‘threshold concentration’, and then gradually abandoned as soon as the nitrate concentration drops below that threshold (Fig. 3). Damage costs D (€/year) resulting from these changes are expected to be borne entirely by tap-water consumers.

$$D = D^P + D^C$$

The benefits B (€/year) resulting from an improvement in groundwater quality are assessed as damage avoided from groundwater contamination. They can be expressed as the difference between damage costs in a baseline situation without AES ($D_{baseline}$) and in a situation with AES (D_{AES}).

$$B = D_{baseline} - D_{AES}$$

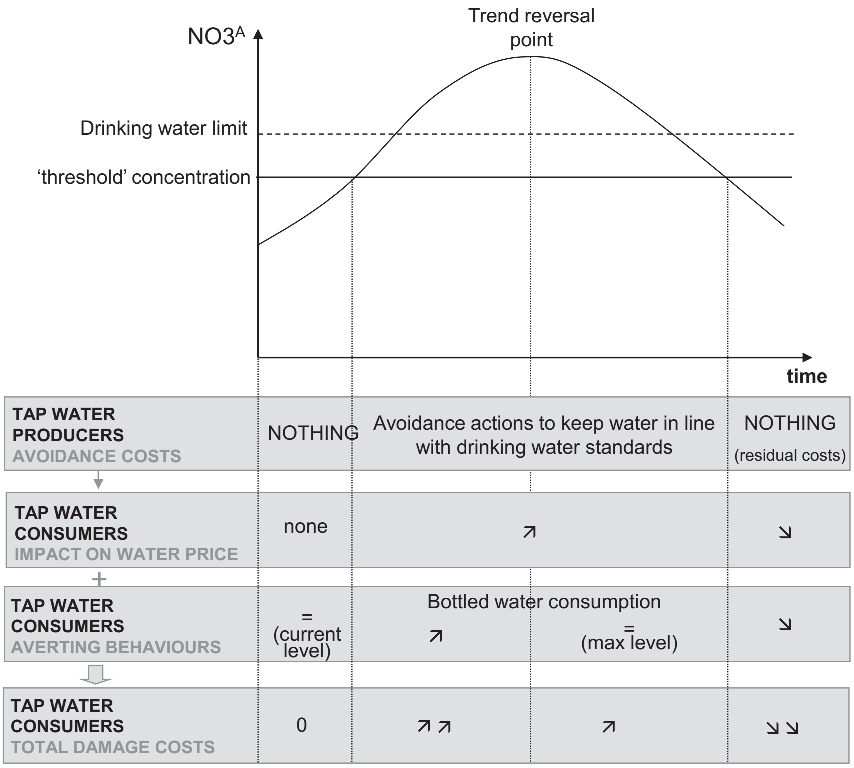

Fig. 3. Economic impacts for tap water consumers resulting from a change in groundwater quality.

3.5. Comprehensive framework for cost-effectiveness analysis and cost-benefit analysis

3.5.1. Definition of the environmental objective

We consider here that 'good' chemical status in groundwater is reached as soon as (i) the drinking-water limit of 50 mg/l is not exceeded at more than 20% of the representative quality monitoring points, and (ii) the average nitrate concentration is decreasing. The WFD requires 'good' chemical status to be achieved by 2015. The European Commission may extend the deadline to 2021 or 2027 in some specific situations (e.g., disproportionate costs, technical infeasibility). M3 can be used to test the effects on groundwater quality of a range of decreases in mean annual nitrate leaching. Step-by-step simulations can provide the required decrease in nitrate leaching as a function of the year in which 'good' chemical status must be reached.

3.5.2. Adjustments in payment levels

In some cases, current payment levels may not be sufficient to obtain satisfactory environmental effects. To address this impediment, we considered new remuneration schemes based on an increase in the payment levels.

Fig. 4 illustrates the simulation of the implementation of an AES that requires a switch to a less productive cropping system. By coupling M1 and M2, the implementation area and the effectiveness of the AES can be expressed as a function of the payment level. At the current payment level, the levels of AES attractiveness and effectiveness are low. When the agri-environmental payment level (AEP) increases, the potential implementation area and effectiveness both increase: the AES becomes attractive first for crop rotation with cereals, then for crop rotation with pulses and, at the highest payment levels, for crop rotation with industrial crops. Let the objective to be reached by this AES be *E**. Crossing the curve of *E* as a function of AEP gives the payment level required, AEP*. New payment levels imply changes in the AES cost-effectiveness ratios.

3.5.3. Selection of cost-effective AES combinations

Selecting the most cost-effective AES combination for reaching a given environmental objective consists of organizing and selecting AES as a function of their capacity to improve groundwater quality at a given cost, i.e., by ranking their cost-effectiveness ratios *R*.

3.5.4. Comparison between the costs and benefits of groundwater quality improvement

Groundwater quality improvements and associated benefits may arise several years after the implementation of measures. Comparing the costs and benefits of achieving a 'good status' thus implies lengthening the time frame of the analysis beyond five years, depending on the time that has to elapse before the benefits appear. In fact, even if AES contracts typically run for five years (and there is no constraint on the farmer's behavior after the end of the contract), the selected cost-effective AES combination may need to be implemented over a longer period to guarantee good groundwater status in the long term. We assume that the costs for AES implementation will decrease by 20% every five years as farmers progressively adapt their farming systems to the AES. The net benefits NB_T (€) expected from implementing the AES combination are assessed as the difference between the total discounted benefits B_T (€) and total discounted costs C_T (€), with a 4% discount rate that will decrease after 30 years.[3]

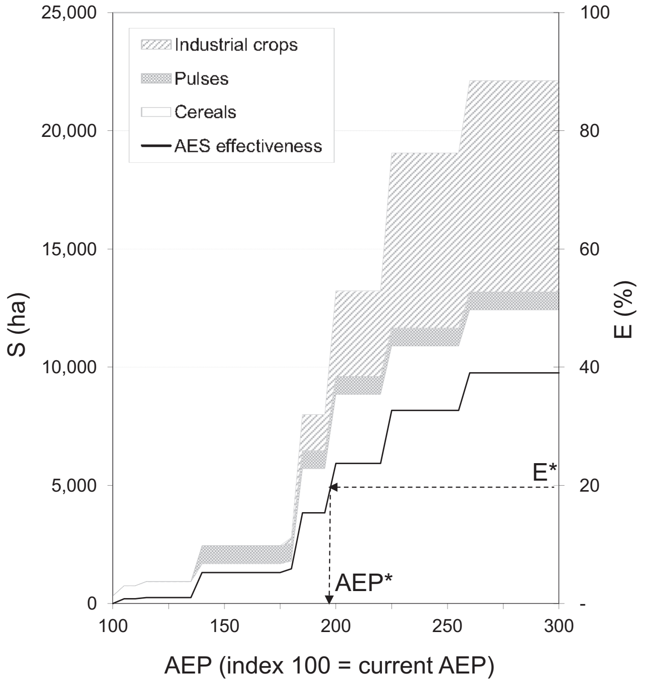

Fig. 4. Change in the AES implementation area (S) and effectiveness (E) as a function of the payment level (AEP). Note: E* is the target effectiveness, AEP* is the payment level required to reach E*.

$$NB_T = B_T - C_T$$

4. Results and discussion

4.1. Defining sustainable nitrate leaching

Nitrate leaching below the root zone is assumed by M2 to have been equal to 15 mg/l in the early 1950s, which corresponds to the nitrate concentrations observed in the groundwater (Hallet, 1998). The concentrations increased steadily from 15 mg/l to 67 mg/l from 1950 to the mid-1980s, when they leveled off at 67 mg/l, in response to the stabilization of nitrogen inputs to crops in Western Europe (Visser et al., 2009). Two theoretical scenarios were tested: a baseline scenario in which current practices continue for fifty years and a scenario 0 with no further agricultural nitrate inputs, beginning in 2010. Simulation of the baseline scenario shows an increase in nitrate concentrations, with no reversal of the trend in coming decades (Fig. 5). These results confirm that unless measures are taken, the Hesbaye aquifer will not reach a 'good' chemical status in the coming years. Results for scenario 0 show that a 'good' status may not be achieved before 2016 even with no agricultural nitrate inputs after 2009. The time scale over which improvements in groundwater quality can reasonably be expected may therefore be much longer than those required by the WFD in the case of the Hesbaye chalk groundwater body. This confirms the results obtained by Jackson et al. (2008) for dual porosity and permeability media such as chalk systems in the UK. In this paper, we propose two alternative environmental objectives: achieving a 'good' chemical status by 2027 (Scenario A) or by 2040 (Scenario B). Step-by-step simulations of M3 show that these environmental objectives imply respectively a decrease of 41% and of 32% in nitrate leaching to the groundwater body as a whole (Fig. 5).

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[3] A 4% fixed discount rate followed by a discount rate that decreases continuously over time after 30 years is recommended by the French Commissariat Général du Plan (2005) for economic valuations of public investments.

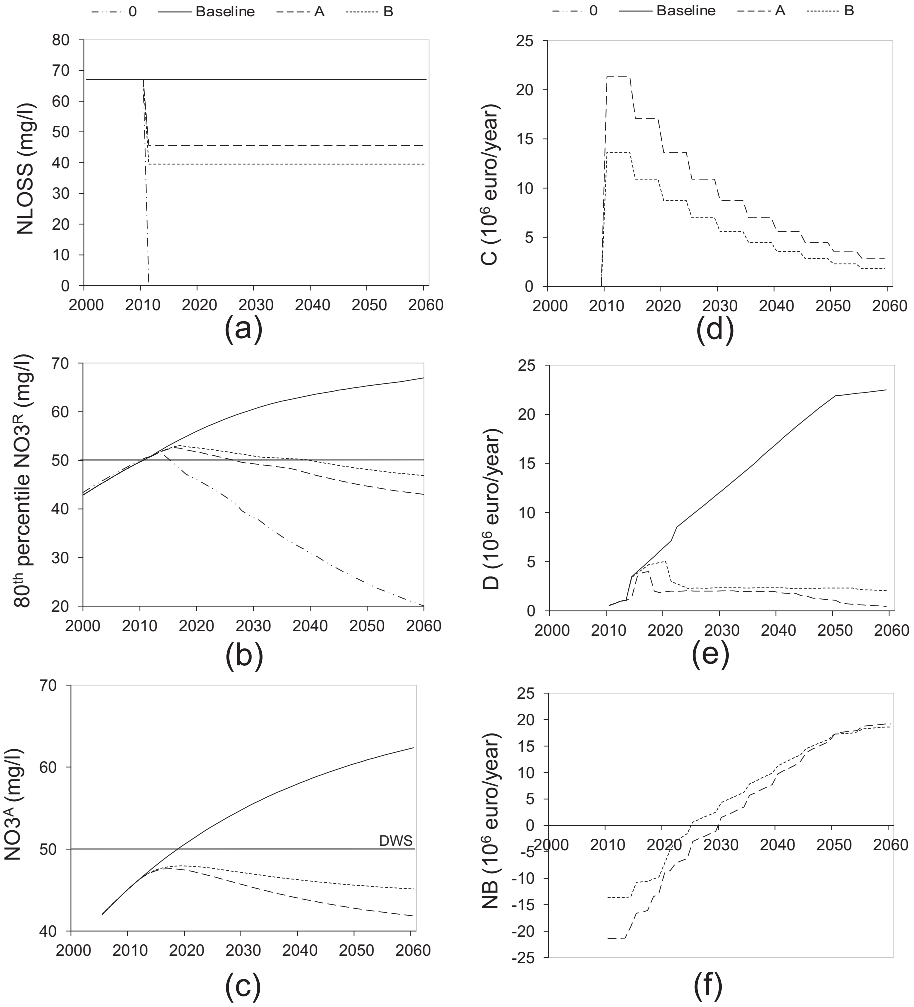


Fig. 5. Comparison between scenario 0, baseline scenario and management scenarios (A and B) in terms of (a) changes in nitrate leaching under the root zone NLOSS, (b) Nitrate concentrations at monitoring points NO_3^R, (c) Nitrate concentrations at abstraction points NO_3^A, (d) Annual costs C, (e) Annual damage costs D and (f) Annual net benefits NB. Note: DWS: Drinking water standard.

4.2. Design of a cost-effective AES combination for achieving 'good' status

The results obtained from M3 show that a drastic reduction in nitrate leaching beneath the root zone is required in order to obtain a 'good' chemical status in the groundwater body. To achieve this objective, important changes in agricultural practices have to occur and cost-effective AES to support such changes must be designed.

4.2.1. Assessing the effectiveness of current AES

Four AES are analysed :

- The conversion of arable land into grassland (GRASS) involves replacing arable annual crops with permanent grass for at least five years. The current payment level of 450 euros per hectare per year.
- The conversion to organic farming (ORGAN) involves switching from current farming practices to organic farming practices that exclude, for example, the use of mineral fertilizers and pesticides. The current payment level of 460 euro per hectare per year.
- The implementation of catch crops (CATCH) involves inserting a catch crop between a winter and a spring crop at least between the 15th of September and the 1st of January. The current payment level is 100 euro per hectare per year.
- The introduction of extensive cereal crops (EXTEN) involves replacing winter cereals with malting barley or rye requiring less fertilization. The payment level is 100 euro per hectare per year.

Table 3 provides details on the estimation of direct costs, effectiveness and implementation area for the four AES. Coupling M1 and M2 shows that with current payment levels, and considering the mean gross margins of the 2005–2009 period, AES are not attractive enough for a 'good' chemical status to be achieved by 2027 or 2040. The environmental effects of their implementation would be unsatisfactory, with changes in agricultural land use over 5000 ha, a reduction in nitrate pressure estimated at 8%, and a cost for the regulator estimated at 0.7 million euros per year (Table 4). Even when considering an 8% decrease in mean gross margins within the study area (2005 gross margins), the attractiveness would remain low with a resulting reduction in nitrate pressure of 9%. Current WFD programs based on AES are likely to be inadequate for reaching the 'good' status objective in the most productive agricultural areas, notably because the schemes are insufficiently attractive.

Table 3
Summary of direct costs, effectiveness and implementation area information for the four AES.

AES		Direct costs	Effectiveness	Implementation area
GRASS	Conversion of arable land into grassland	Difference in gross margins between five years of grassland (i.e., 606 €/ha/year) and the current pattern of crop rotation	Difference in the mean annual nitrate leaching between five years of grassland (i.e., 25 mg/l) and the current pattern of crop rotation	Relevant for arable land where the payment level covers direct costs for farmers Implemented on 70% of the relevant area
ORGAN	Conversion to organic farming	Difference in gross margin between an eight-year organic farming rotation (e.g., temporary grass/temporary grass/wheat/barley/sugar beet/pulses/cereals/barley : 1000 €/ha/year) and the current pattern of crop rotation 35% loss in yields (2007–2013 Walloon Rural Development Plan) uncompensated by higher prices the two first years (i.e., 280 €/ha/year)	Difference in the mean annual nitrate leaching between an eight-year organic farming rotation with a 30% decrease (Tuemisto et al., 2012) in nitrate leaching due to the absence of mineral fertilizer (i.e., 39 mg/l) and the current pattern of crop rotation	Relevant for arable land where the payment level covers direct costs for farmers Implemented on 70% of the relevant area
CATCH	Implementation of catch crops	5% loss in spring crop yields, costs of seeds, soil preparation and sowing, savings from reduced nitrogen fertilization (2007–2013 Walloon Rural Development Plan)	Decrease in the mean annual nitrate leaching for relevant crops by 30% (based on results from Vanderberghe and Marcoen, 2004)	Only relevant for spring cultivated crops (e.g., spring barley, maize, potatoes, sugar beet, chicory) where the payment level covers direct costs for farmers Implemented on 70% of the relevant area
EXTEN	Introduction of extensive cereal crops	Difference in gross margins between malting barley requiring less fertilization (i.e., 908 €/ha/year) and winter cereals	Difference in the mean annual nitrate leaching between spring barley (i.e., 35 mg/l) and winter cereals (i.e., 55 mg/l)	Only relevant for winter cereals where the payment level covers direct costs for farmers Implemented on 70% of the relevant area

4.2.2. *Assessing the cost of achieving ‘good’ chemical status*

Step-by-step simulations were undertaken to determine the payment levels that would guarantee a ‘good’ groundwater status by 2027 or 2040. We selected the two most cost-effective AES combinations (Table 4). The corresponding reduction in nitrate leaching is found to be achieved for the whole simulation period (2010–2060). Both combinations include the four proposed AES. Although AES involving only changes in cropping practices (EXTEN and CATCH) are the most cost-effective, their potential implementation area across the catchment is small, even with higher payment levels. Implementing AES that also involve land-use changes (GRASS and ORGAN) is therefore required if the objectives are to be reached, even though their cost-effectiveness ratios are much higher. The attractiveness and resulting effectiveness of ORGAN and GRASS are highly dependent on their payment levels: at the current level, GRASS, for instance, could be implemented over 82 ha, while doubling the payment level could increase implementation of the measure to 13,998 ha. However, implementing GRASS and ORGAN reduces the potential implementation areas for EXTEN and CATCH, since these AES are not compatible on the same parcel. The resulting change in agricultural land-use is expected to be large, especially with the A combination, resulting in the conversion of 42% of the arable land into grassland, an increase in cereal areas, and an increase in longer crop rotations promoted by conversion to organic farming (Fig. 6).

Table 4
Cost-effectiveness analysis results of AES combinations.

		AEP	S	E	C^R	C	R	Rank
		€/ha/year	ha	%	10^6€/year	10^6€/year		
Current AEP level	CATCH	100	4789	8%	0.5	0.7	86	1
	GRASS	450	82	<1%	<0.1	<0.1	99	2
	ORGAN	460	378	<1%	0.2	0.3	1677	3
	EXTEN	100	–	–	–	–	–	–
	Total			8%	0.7	1.0	130	
Combination A	CATCH	140	2196	3%	0.3	0.4	122	1
	EXTEN	295	473	1%	0.1	0.2	225	2
	ORGAN	667	1596	3%	1.1	1.6	517	3
	GRASS	945	13,998	34%	13.3	18	529	4
	Total			41%	14.8	20.2	493	
Combination B	CATCH	140	3325	5%	0.5	0.5	99	1
	EXTEN	295	349	1%	0.1	0.2	159	2
	ORGAN	598	504	1%	0.3	0.4	428	3
	GRASS	860	9567	25%	8.2	11.7	492	4
	Total			32%	9.1	12.8	400	

During the five first years of implementation, such programs would cost from 9.1 million euros (combination B) to 14.8 million euros (combination A) per year for the regulator i.e., 11–18 times more than the average budget currently provided in the Walloon Rural Development Plan. If payment levels are adjusted to increase AES attractiveness, WFD programs built on the basis of AES combinations may have difficulty in reaching WFD objectives, because of budget constraints. For these programs to be effective, the budget allocated must be much higher than at present, with total payments ranging from 12,000 to 19,000 euros per farm per year. A budget increase of this size would require a complete overhaul of the European Common Agricultural Policy (CAP). This would be even more true in the event of an increase in crop prices: M1 shows that the costs would increase by 19–23% for a 10% increase in mean gross margins (2007 gross margins) within the study area.

From a society's viewpoint, selected AES combinations would cost 12.8 million euros (combination B) to 20.2 million euros (combination A) per year during the first five years. Total discounted costs over a 50-year period would range from 172 million euros (combination B) to 272 million euros (combination A), i.e., 117 to 186 euros per household in the Walloon Region.

Achieving the ‘good’ status objective by 2027 rather than 2040 implies a 58% increase in the costs. From an economic viewpoint, if these costs are not offset by higher benefits, achieving ‘good’ status by 2040 would be preferable.

4.3. *Benefits of protecting the aquifer*

The highest (use-related) benefits from improving groundwater quality in the Hesbaye aquifer are expected to occur in the public water sector. Three drinking-water companies exploit the Hesbaye aquifer for drinking-water production, using two distinct types of infrastructure: nine production wells (3 million cubic meters withdrawn per year) and a 48-km network of tunnels excavated in the chalk at a depth of 30–60 m to supply two reservoirs and four wells (17 million cubic meters withdrawn per year). In the baseline

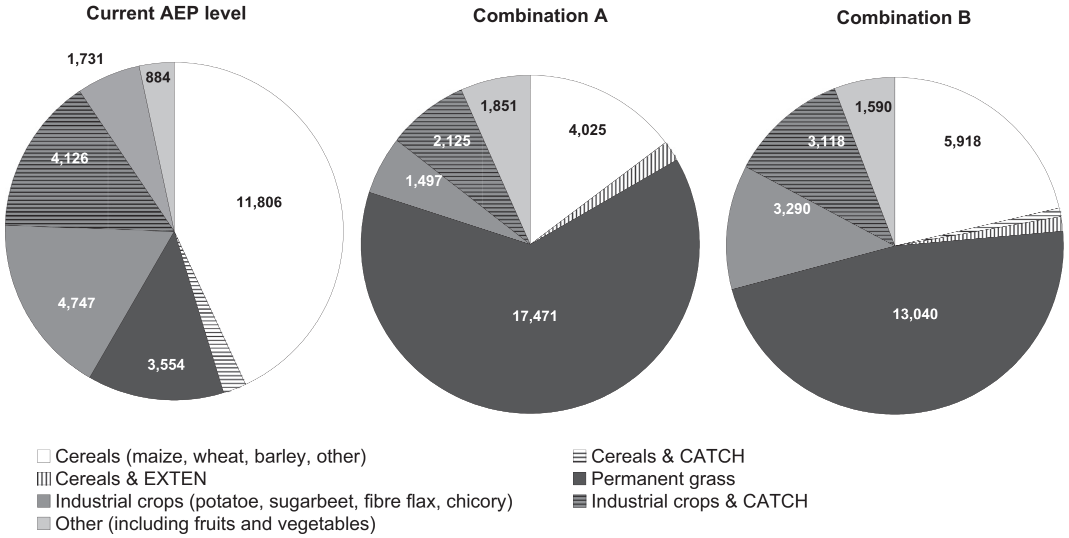


Fig. 6. Effects of AES combinations A and B on agricultural land-use (in hectares).

scenario (no measures), nitrate concentration is expected to increase progressively in all production wells and tunnels, with 93% of the volume withdrawn from the study area exceeding 50 mg/l by 2015. Simulation of the A and B combinations shows that the average nitrate concentration in production wells will reverse before 2020 (Fig. 5), with a maximum affected volume ranging between 17 and 19%.

Three types of potential avoidance actions for public water producers were analyzed, depending on the duration of contamination and the types of production equipment: (i) dilution; (ii) treatment by reverse osmosis; and (iii) treatment by denitrification. While dilution and treatment by reverse osmosis can be considered for the drinking water produced from the tunnels, denitrification is proposed only for production wells.

- The dilution of groundwater involves purchases of surface water with lower nitrate concentrations. The dilution rate should not exceed 10%, otherwise additional treatment would be required (for pH readjustment), making this action relevant in a short-term pollution situation or in the case of a groundwater nitrate concentration only slightly higher than the threshold value. With this option and depending of the level of dilution that is required, the additional cost for tap-water production would range from 0.05 to 0.09 euros per cubic meter produced (includes the purchase and transfer of surface water minus the production costs for the water abstracted from the tunnel).
- Treatment by reverse osmosis is relevant in the event of longer-term pollution (more than five years) and consists of carrying out overall water treatment, possibly coupled with a water-softening process. Local estimates of additional costs required for drinking-water production with this option (including investment and running costs of the treatment unit) range from 0.16 to 0.26 euros per cubic meter produced.
- Treatment by denitrification is to be considered only in the case of contaminated production wells. Observed data in the Walloon Region show that the additional cost (including investment and running costs of the treatment unit) ranges from 0.17 to 0.22 euros per cubic meter produced.

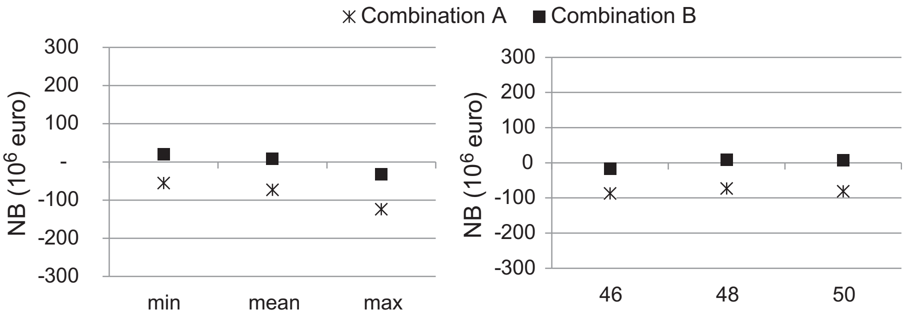
Averting behaviors may be considered by private households which lose confidence in tap-water quality in the event of groundwater pollution. Twenty percent of the Walloon population do not trust the quality of distributed tap water and 60% drink bottled water rather than tap water (Aquawal, 2005). In our study we assumed a 2.6% increase in daily household consumption of bottled water in the case of groundwater degradation, which corresponds to the annual rate observed in 1990 in the Walloon Region (Aquawal, 2005), an average bottled water price of 0.4 euros per litre, and the 2008–2060 population forecast for Liege Province.

If no measures are taken to protect the aquifer against nitrate pollution, annual damage directly related to drinking-water production is expected to increase steadily over time (Fig. 3). Total discounted damage could reach 240 million euros, i.e., 4.8 million euros per year. This damage cost represents 2500 euros per household supplied by tap water from the Hesbaye aquifer (164 euros per household in the Walloon Region). Implementing the AES combination A or B would reduce this by 83% or 75% respectively, leading to benefits estimated at 3.6 to 4 million euros per year. If we assume that avoidance actions and averting behaviors are adopted sooner (threshold value: 46 mg/l) or later (threshold value: 50 mg/l), benefit values would remain quite similar and range respectively between 3.1 and 3.7 (46 mg/l) or 3.6 and 3.8 (50 mg/l) million euros per year.

Indirect use and non-use values may also be associated with an improvement in groundwater quality. These values can be assessed by applying contingent valuation techniques. Bouscasse et al. (2009) have proposed an estimation of benefits by transferring values obtained with the contingent valuation method in the BRIDGE EU research project to the Hesbaye aquifer. Willingness to pay is estimated at 34 to 52 euros per year per household, bringing an aggregate benefit from groundwater quality improvement ranging from 3.2 to 4.9 million euros per year. These values, which

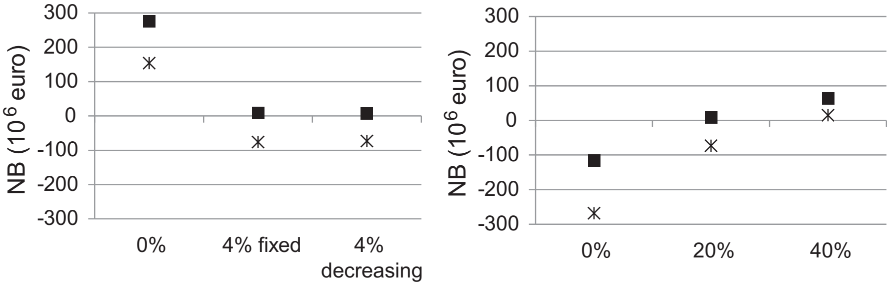
Table 5
Cost-benefit analysis results of AES combinations.

	Baseline	Combination A	Combination B
Y	–	2027	2040
E	0%	41%	32%
C_T (10^6 €)	–	272	172
D_T (10^6 €)	240	41	60
$C_T + D_T$ (10^6 €)	240	313	232
NB_T (10^6 €)	–	−73	+ 8



(a) Gross margin

(b) Threshold concentration (mg/l)



(c) Discount rate

(d) Adaptation rate

Fig. 7. Sensitivity of net benefits estimates to (a) gross margins: Values of the 2005–2009 period, min: 1548 €/ha/year (year 2005); mean: 1684 €/ha/year; max: 1849 €/ha/year (year 2007), (b) Threshold concentration, (c) Discount rate and (d) Adaptation rate.

incorporate both use and non-use values, are comparable to those obtained by the avoidance cost method (from 3.6 to 4 million euros). They show that benefits for the public water sector may be the highest to be expected for this aquifer.

AES may not only have a positive impact on groundwater resources but also on associated surface water resources, biodiversity, and landscape. The analysis presented here does not take into account the economic value of these additional benefits of groundwater protection: the figures given in this paper should thus be considered as a lower bound assumption of the benefits to be expected from implementation of the measures.

4.4. Costs versus benefits of protecting the aquifer

A comparison of costs and benefits indicates that positive net benefits for society as a whole may be achieved only by the B combination (Table 5). The benefits expected from combination A may not offset the higher costs of AES implementation. From an economic perspective, delaying the year in which the Hesbaye aquifer should reach a ‘good’ status from 2027 to 2040 seems to be preferable. However reaching a ‘good’ status by 2040 (combination B) does not create significant net benefits: it mainly transfers costs that would have been borne by tap-water consumers (2500 euros per household supplied by the Hesbaye aquifer) to European and Walloon tax payers (117 euros per household in the Walloon Region) via the regulator in charge of implementing agri-environmental schemes.

Net benefit estimates are highly sensitive to the underlying assumptions made when comparing costs and benefits over such a long time period. In particular, two parameters have major influence on the estimates: the choice of the discount rate and of the rate at which costs decrease as the farmers adapt to the new practices. A zero adaptation rate would lead to negative net benefits for both combinations (−268 to −116 million euros), while the absence of a discount rate would result in higher positive net benefits ranging between 154 and 276 million euros (Fig. 7). The influence of these parameters on net benefit estimates is much higher than the effects of variations in gross margins or threshold concentrations. In all cases, however, delaying the 2027 objective to 2040 is preferable from an economic viewpoint.

5. Conclusion

This paper describes the development and application of a hydro-economic model for identifying the most cost-effective program of AES for maximizing the net benefit for society at groundwater-body scale. The results show that AES as designed at present may not be adequate for achieving the ‘good’ groundwater status required by the WFD in the case of the Hesbaye aquifer. Reaching a ‘good’ status by 2027 at the latest would demand a substantial change in AES design, involving costs that may not be offset by benefits in the case of chalk aquifers with long renewal times. From an economic standpoint, delaying the deadline for reaching ‘good’ status to 2040 would be preferable for the Hesbaye aquifer.

This method contributes to the EU’s WFD implementation process by providing insights for the definition of cost-effective programs of measures for controlling diffuse groundwater pollution. The integrated approach proposed can easily be implemented by water managers to build realistic and cost-effective WFD programs of measures. The key obstacle for such integrated models at the scale of a large river basin may be the lack of hydrogeological modeling tools for all groundwater bodies, even though this kind of model is becoming more common. This could be overcome by developing several case studies that are representative of the diversity of hydrogeological contexts, and extrapolating the results to similar situations.

There are also a few caveats and limitations to the methodological approach presented here, which must be stressed. Firstly, this analysis focuses on AES only. Although these represent the majority of the WFD measures currently undertaken by Member States, other policy options for reducing nitrate concentrations might be evaluated (e.g., fertilizer taxes and fertilizer standards) and compared, to determine the most cost-effective options. Secondly, a simplified approach was used for estimating nitrogen contents in the leach water. Although this approach has the advantage of being easy to use at the scale of a water body or river basin, additional work would be required to develop the agronomic part of the model. In fact, nitrate leaching estimates are expected to have a high influence on the four modules of the hydro-economic model. Thirdly, several sources of uncertainty are associated with each module (e.g., model structure uncertainty, parameter values uncertainty, and input data uncertainty). A comprehensive analysis of the diversity of sources of uncertainty and of their effects on the results of the economic analysis would be of great interest: further research should be carried out in this direction.

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