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Restoring groundwater quality at the drinking water catchment scale: a multidisciplinary and participatory approach.

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Abstract:

Preserving or restoring the quality of groundwater resources with regard to nitrate is a major challenge. To date, useful and easily applicable tools to identify the best measures to implement at local scale are lacking. An innovative methodology is proposed to identify cost-effective restoration measures at the drinking water catchment scale. The methodology is based on the articulation of two tools: a model simulating nitrate groundwater contamination time series and an economic evaluation, within a participatory approach. It was applied to a representative drinking water catchment in Northwest France that has been affected by nitrate contamination for decades. Five scenarios of measures (changes in fertilization and intercropping practices, or in cropping patterns) were co-constructed with stakeholders, evaluated in terms of cost and impact on groundwater nitrate concentration, and discussed with stakeholders. Overall, two scenarios stand out. Introducing hemp in crop rotations is the only scenario generating an economic benefit, but for a very low impact on nitrate concentration (decrease of 4 mg/l by 2050 for 10% of hemp in crop rotations). Introducing alfalfa in crop rotations is the most effective measure to decrease nitrate concentration (decrease of 23 mg/l by 2050 for 20% of alfalfa in crop rotations), and for a moderate cost compared to the other scenarios (25 to 51 €/ha/year). Results show that substantial changes in cropping patterns – more important than those imagined initially by stakeholders (e.g. converting 40% of cropland to alfalfa) are needed to restore groundwater quality targets in the medium-long term. Measures deemed promising and achievable by the stakeholders proved to be insufficiently effective. The approach developed has been shown to provide valued and trusted information to stakeholders and to objectify debates. Stakeholders have shown interest in the evaluation of costs and further socio-economic information, in addition to the evaluation of the effectiveness of measures on groundwater quality, validating the multidisciplinary dimension of the approach. The approach has the advantage of being easy to implement, and is therefore applicable to other study sites where needed.

Keywords: Agricultural practices, Cost-effectiveness analysis, Groundwater, Nitrate transfer modelling, Participatory process

1. Introduction

Groundwater is the most important resource for drinking water production worldwide (Guppy et al., 2018). For instance, it represents about 60% of drinking water resources on average in Europe, and up to 100% in certain countries as Denmark or Austria (EurEau, 2021). Diffuse agricultural pollution, in particular nitrates, is one of the main pressures affecting groundwater bodies worldwide. This pollution threatens the sustainability of the services associated with groundwater, in particular the ability to produce high-quality drinking water. It is recognized that nitrate in drinking water is associated with adverse health outcomes (Ward et al., 2018; Essien et al., 2022). To address that threat, the World Health Organization has set a drinking water guideline of 50 mg/l (as NO₃).

In response to the deterioration in groundwater quality, drinking water utilities have historically had to take several adaptation measures in order to maintain the supply of water whose quality complied with health standards – e.g. installation of treatment plants, building of interconnection infrastructures or use of new water resources (Bommelaer et Devaux, 2011; Hérivaux et Gauthey, 2018). However, these technical measures are costly for the water consumer and they do not restore the quality of the groundwater resource. They cannot be the only solution and groundwater quality preservation or restoration measures must also be considered.

In the European Union in particular, several directives explicitly require the implementation of preventive actions to restore or avoid the degradation of the quality of groundwater resources since the 1991 Nitrates Directive (91/676/EEC). The Water Framework Directive (WFD - 2000/60/EC) and its associated Groundwater Directive (GWD - 2006/118/EC), require member states to ensure that all their surface water and groundwater bodies are in good chemical status by 2027 at the latest. They call for the implementation of cost-effective action programmes, prioritizing measures according to their capacity to improve the state of water resources for a given cost. The new drinking water directive (DWD - 2020/2184) also encourages the use of these preventive measures with the obligation for local authorities to implement water safety management programmes.

In consequence, numerous actions have been carried out in Europe since the 1990s to restore the quality of water with respect to nitrate (Tzilivakis et al., 2020). However, despite these efforts, many groundwater bodies still do not meet the good quality status. Top-down regulation is not enough to tackle the issue (Belmans et al., 2018). There is a need for ex ante evaluation tools, in order to identify appropriate mitigation measures for these groundwater bodies where efforts have remained unsuccessful.

While cost-effectiveness analysis (CEA) has been described as an appropriate tool to select restoration measures to mitigate diffuse agricultural pollution (Balana et al. 2011; Alcon et al., 2021), it has so far been unsuccessful in helping to define local action plans at the drinking water catchment scale.

Indeed, CEA has often been carried out without taking into account the local specificities of the territories (Feuillette et al., 2016). There is a need for bottom-up approaches to identify measures that are more adapted to the local context (Van Grinsven et al., 2016; Voinov and Brown Gaddis, 2008) rather than generic solutions, and that involve relevant stakeholders (Belmans et al., 2018). Engaging stakeholders can help to both develop solutions relevant to the local situation (Voinov and Brown Gaddis, 2008) and increase the acceptability of catchment mitigation plans (Bouraoui and Grizzetti, 2014).

The implementation of mitigation measures can be in conflict with the interests of local stakeholders (Wiering et al., 2020). Their acceptance of the measures can be difficult, especially if they lack concrete elements to quantify the expected impacts of these measures. Effects that do not meet expectations can also be a source of discouragement for actors who have been implementing actions for several years. This is especially true for groundwater where the time lag between the change of agricultural practices and the impact on groundwater quality can be several years or even decades (Baran et al., 2021; Meals et al., 2010; Gutierrez and Baran, 2009; Sohler and Degré, 2010; Surdyk et al., 2021a).

Yet, while CEA should theoretically be based on the evaluation of the effectiveness of each restoration action in terms of groundwater quality improvement (Berbel et al., 2011; Martin-Ortega, 2012), few hydrogeological tools have been used so far to carry out cost-effectiveness analysis evaluating the improvement in groundwater quality. The effectiveness of action programmes has often been evaluated in terms of the reduction in the polluting pressure exerted on groundwater (Hérivaux et al., 2013) rather than its impacts, without taking into account groundwater dynamics, the system's purification capacities and its inertia. There is a need for CEA approaches that evaluate the

effectiveness of potential mitigation measures in terms of nitrate concentration rather than just in terms of pollution pressure, and take into account the long term.

Finally, modeling approaches dealing with diffuse pollution and incorporating both hydrogeological and economic evaluations have been mostly developed at the regional or aquifer scale (Graveline and Rinaudo, 2007; Ledoux et al., 2007; Peña-Haro et al., 2009, 2010; Viavattene, 2006; Hérivaux et al. 2013; Hérivaux et al., 2014), not at the drinking water catchment scale. It might be more cost-effective to target restoration measures on the drinking water catchment, and groundwater source protection areas have been recommended in the United States, the European Union and more widely internationally (Foster and Chilton, 2021). To date, useful and easily applicable tools to identify the best actions to implement at this local scale are lacking.

To fill those needs, we propose an innovative easy-to-implement methodology to identify cost-effective restoration measures that: 1) focuses on the drinking water catchment scale, 2) measures the effectiveness of potential measures in terms of nitrate concentration evolution over time, and 3) considers solutions adapted to the local context (i.e. agricultural, hydrogeological and socio-economic situations), involving local stakeholders. This methodology is based on the articulation of two tools: a lumped model simulating nitrate groundwater contamination time series and an economic evaluation, within a participatory approach (Figure 1). This article describes the main components of the methodology and its application to a representative drinking water catchment whose quality has been degraded by nitrate for decades.

2. Study site

The drinking water catchment of Pentvert is located in the department of Sarthe, in north-west France (Figure 2). The borehole was built in 1980 and has been exploited for public water supply since 1990. Abstracted volumes are about 1 Mm³/year. Nitrate concentrations are currently higher than 80 mg/l, well above the European DWD limit of 50 mg/l.

The perimeter of the study site corresponds to the drinking water protection area (or wellhead protection area), defined by prefectural decree in 2008, which covers 27 sq. km. Agricultural surfaces represent 90% of the area (2419 ha, i.e. 24.19 sq. km), belonging to 80 farms located or partly located on the perimeter. Wheat and barley are by far the most widespread crops, covering more than half of the agricultural area, followed by rapeseed (about 15% of the area) and maize (about 10%; 2/3 grain and 1/3 silage).

The borehole is 20 meters deep and taps an unconfined aquifer located in fissured limestone. Groundwater levels have intra-annual fluctuations of less than 1 m, the low water period generally occurring in August-September. The thickness of the unsaturated zone in the vicinity of the borehole is around 10 m. The average rainfall is 699 mm/year while average potential evapotranspiration is 739 mm/year (calculated over the period 1988-2016). The soil average thickness is 0.45 m; the water holding capacity is 50 mm.

When the Pentvert borehole was drilled, average nitrate concentration was above 60 mg/l. A first drinking water catchment area was delineated, leading to the conversion of about 1% of the cultivated area into poplars plantation requiring no nitrogen input at the borehole vicinity. However, concentration increased over the next decade, reaching values of 90 mg/l in 1990. A denitrification treatment plant was built in 1993 for public water supply. Following the EU

Nitrates Directive, Pentvert was classified as a “vulnerable zone” and several types of measures were implemented, aiming at recovering groundwater quality to enable the production of drinking water meeting quality standards. In this regulatory context, five successive programmes of actions were implemented from 1994 to comply with regulations (fertilizer spreading limitation, cover crops, buffer strips, etc.). In parallel, several contractual action programmes were also implemented locally between 1991 and 2015 (catch crops, diversification of crops, limitation of fertilisation), accompanied by actions to raise awareness and disseminate agricultural practices. By opposition, as a result of Common Agricultural Policy and the evolution of the agricultural sector, from the 1990s grassland surfaces decreased with the decrease of cattle farming in the area (from 20% in 1988 to 11% in 2010), while crops surfaces, especially rapeseed, increased. Groundwater nitrate concentration kept increasing, exceeding 100 mg/l in 2000. From 2004 onwards, additional contractual programmes were implemented (monitoring, agronomic advice, fertilization limitation, no bare soil in winter, crop diversification). From 2003-2004, nitrate concentration has slowly decreased, but it remains higher than 80 mg/l to this day. Further details on historical nitrate concentrations and the chronology of historical action programmes are available in Supplementary Materials (Appendix 1).

Several action programmes have already been implemented in the study area over the past decades; they have allowed an inflection of the concentration increase trend, but have not been effective enough to reach below the threshold value of 50 mg/l. Furthermore, due to the inertia of the hydrological system, it takes several years to see if an implemented mitigation measure will have an effect on groundwater nitrate concentration. There is a need for identifying potential further actions in Pentvert and for evaluating them ex-ante to inform decision making. This makes it a good case study to apply the proposed method, all the more so as the hydrogeological and agricultural contexts of Pentvert are representative in Europe.

3. Method

3.1. Overview of the approach

The approach developed combines nitrate transfer modelling and economic evaluation, embedded in a participatory process (Figure 1): ① scenarios of agricultural measures are co-constructed with stakeholders, building on a shared review of the past actions already implemented and the current situation; ② data and hypotheses necessary for the evaluation of the impacts of the scenarios are collected, in concert with stakeholders; ③ scenarios are evaluated in terms of effectiveness and cost, as well as in terms of more qualitative technical and socio-economic considerations; ④ depending on evaluation results, additional exploratory scenarios may be considered; and finally ⑤ evaluation results are presented to stakeholders for discussion.

These five steps are described in more details through their application to the representative study site of Pentvert.

3.2. Application of the approach to Pentvert drinking water catchment

3.2.1. Co-construction of scenarios

A participatory workshop was organized in September 2017, bringing together 13 stakeholders concerned by the nitrate issue, including farmers, the Chamber of Agriculture of Sarthe, the drinking water company operating the

Pentvert water plant, departmental state services in charge of agriculture and environment, regional state services in charge of health, the departmental council and the regional Water Agency. The objective was to build scenarios of measures aiming to sustainably recover good groundwater quality in the Pentvert catchment in respect to nitrates. The workshop was organized in three steps.

First, the research team presented an overview of historical nitrate concentration trends in Pentvert, and of historical measures having already been implemented so far (Appendix 1) and their cost, as well as information on the current land use and agricultural practices in the catchment. This allows every participant to start the participatory process with a common level of information necessary to start co-constructing scenarios of measures.

Second, participants carried out individual brainstorming on potential measures that could further be implemented, placing their ideas on post-its. Individual contributions were then collected, collectively discussed and synthesized, grouping similar ideas into clusters on a board, following the metaplan process (Davies et al., 2012). This step identified three main types of measures to be investigated.

Third, participants worked in three sub-groups, one for each main type of measures, in order to come up with a technical description of potential actions and to specify possible implementation rates on the Pentvert territory. Then each sub-group presented their results to the rest of the group for plenary discussion.

Following the workshop, the research team synthesized the results of the workshop into “Action Sheets”, complemented by a technical feedback on the capacity of simulating the different actions with the BICHE nitrate transfer model (Thiéry and Seguin, 1985). These sheets were distributed to the participants to collect their feedback. Following these interactions between participants and modellers about “what is desired and what is feasible” (Korfmacher, 2001), five scenarios were finally produced, which were deemed the most promising in terms of groundwater quality improvement and feasible on the Pentvert territory by stakeholders, and could be simulated with the nitrate transfer model from a technical point of view. Each scenario consists of a choice of cropping pattern and associated agricultural practices.

3.2.2. Participatory data collection and validation

The collection of technico-economic data necessary to evaluate the impacts of the scenarios in terms of groundwater nitrate concentration and in terms of costs (land use and crop repartition, sowing and harvesting dates, crop yields, fertilization doses and application dates, crop prices, production costs, etc.) was carried out in two stages. First, existing data was compiled from national databases (Agreste, 2018), national technical publications (Valé 2006, COMIFER, 2013), and local data (Chambre d’Agriculture de la Sarthe, 2018; Chambre d’Agriculture de la Mayenne, 2016). Participants from the Chamber of Agriculture of Sarthe contributed technico-economic data their institution had collected through a survey among farmers. Telephone interviews were also conducted with farmers who were experts in specific crops.

Then, a technical meeting was organized in September 2018 with the Chamber of Agriculture of Sarthe and farmers participating in the study to synthesize the various sources of information and validate the data and hypotheses to use for the evaluation. The objective in involving stakeholders in data collection and validation was twofold: to build on

local expertise and ensure that the data used for the evaluation was representative of the local Pentvert area, and to foster trust in the evaluation process and thereby improve the acceptability of its results.

3.2.3. Scenario evaluation

To assess their impact on the evolution of groundwater nitrate concentrations, the co-constructed scenarios were simulated with the nitrate transfer model BICHE (Thiéry and Seguin, 1985). BICHE is a lumped model, representing the watershed as a cascade of surface, intermediate and deep compartments (Appendix 2). Processes are represented by simple laws, whose parameters are specific to each compartment. BICHE simulates the evolution of groundwater nitrate concentration at the drinking water well by considering the catchment as a whole, without spatial discretization. It does not require a comprehensive hydrogeological survey of the study area. Through a calibration phase, model parameters are adjusted to fit the observed time-series (piezometric levels and nitrate concentrations). As a hydrological lumped model, it is designed to evaluate long term trends (not to reproduce short-term variations). The BICHE model was selected for its ease of use and its low input data requirement. It was successfully calibrated and evaluated on the Pentvert catchment for the period 1985-2017 (see Surdyk et al., 2021b - case study "limestone site") before it was used for scenario simulation. A validation test based on a 5-year extension of the dataset was performed, proving the robustness of the calibration process. Further information, including input data presentation and sensitivity analysis, is also available in Surdyk et al. (2020).

Scenario simulations were performed with the BICHE model from 2018 to 2050, at a monthly time-step. Future climate was represented by a repetition of a sequence of past years: precipitation and evapotranspiration monthly data from 2000 to 2009 (data measured at the meteorological stations of Météo-France, the national meteorological and climate operator) were repeated from 2018 till the end of the simulation. This period of 2000-2009 was selected because it contains both dry and wet years and accounts well for inter-annual climatic variability in the Pentvert area, under the hypothesis that the impacts of climate change on future monthly average precipitation will be negligible in this area.

The cost of the co-constructed scenarios was evaluated in terms of cost for farmers. It was assessed in terms of the semi-net margin differential between current practices and the scenario considered. The semi-net margin indicator allows for the integration of specific harvesting and drying costs, which vary greatly between the different crops of the study site. It also accounts for costs associated with changes in practices (intercrop, fertilization) for a given rotation. Given the volatility of agricultural commodity prices, the impact of price variability on the cost of measures was also examined, as well as the impact of yield variability. The semi-net margins of the different crops, reconstructed following the data collection method described above and used as a basis for estimating the cost of scenarios, are available in Supplementary Materials (Appendix 3).

Qualitative information about other positive and negative technical or socio-economic aspects to bear in mind when evaluating the scenarios was synthesized from the data collected through the participatory process described above.

3.2.4. Additional exploratory scenarios

Depending on the evaluation results of the co-constructed scenarios, additional scenarios may be designed by the research team and evaluated, in order to provide further information to the stakeholders. The additional exploratory

scenarios may be designed for different purposes: to provide insight on the inertia of the hydrosystem, to provide information on the potential resizing of the co-constructed scenarios when they prove under or over-effective, to provide information on the potential synergy between co-constructed scenarios etc.

In the case of Pentvert, additional exploratory scenarios were produced by the research team to provide further information to stakeholders (Section 4.2).

3.2.5. Discussion with stakeholders

Impacts of all scenarios in terms of effectiveness, cost, and additional qualitative technical and socio-economic information were presented to stakeholders and put to discussion during a final workshop in April 2019.

4. Results

The approach developed produces three types of results: 1) the scenarios of measures co-constructed by stakeholders, 2) the evaluation of the impacts of the different scenarios in terms of both effectiveness to reduce groundwater nitrate concentration and costs to farmers, and 3) the results of the whole approach in terms of insights for stakeholders and for the territory.

4.1. Co-constructed scenarios of measures

The participatory process led to the design of five scenarios (Table 1). Two of them relate to changes in fertilization and intercropping practices, while the remaining three consist in changes in cropping patterns - increasing the share of certain crops or introducing new crops:

- “Short cover”: Implement cover crops (nitrate catch crops) during all short intercropping periods ;
- “N splitting”: Split nitrogen mineral fertilization of wheat (one additional application for a given total dose);
- “Sunflower”: Increase the share of sunflower in the agricultural area from 5% to 15%;
- “Hemp”: Introduce hemp in crop rotations to reach a share of 10% of the agricultural area;
- “Alfalfa”: Introduce alfalfa in crop rotations to reach a share of 20% of the agricultural area.

For the two scenarios implying changes in technical practices, the cropping pattern remains the same as in the current situation, only the fertilization and intercropping practices do change. In the “Short cover” scenario, covers are put in place during all short intercrops (pea/wheat, sunflower/wheat, rapeseed/wheat, wheat/wheat, corn/wheat), over the entire study area, in addition to the already mandatory long intercrops (Nitrates Directive). Unlike long intercrop (when the next crop is sown in the spring after an autumn harvest), in the case of short intercrop the next crop is sown in autumn, which leaves less time for cover development. Participants decided that the cover crop would be a mix of mustard, phacelia and buckwheat, with an expected yield of 2 tons dry matter (tDM) per hectare.

In the “N splitting” scenario, wheat mineral fertilization is split into an additional application instead of current application practices, on the whole wheat area. For field-crop farms, which represent 60% of the cultivated area, it will consist of four mineral nitrogen applications between February and April (instead of three). For breeding farms, representing 40% of the cultivated area, it will consist of three mineral nitrogen applications in March and April

(instead of two). The scenario simply consists in further splitting the fertilization current application (postponing the application of 30 kg of N/ha from March to April), without modifying the total crop intake.

For the three scenarios implying changes in crop repartition, participants decided that introducing the new crops through the lengthening of existing crop rotations would be more realistic than introducing new rotations. Two main rotations pre-exist in the Pentvert area: (1) a “rapeseed/wheat/straw cereal” rotation, representing 52% of the agricultural area (the straw cereal can be wheat or barley, but this rotation was considered as “rapeseed/wheat/wheat” for the sake of simplification); (2) a “corn/wheat/spring crop/wheat” rotation, representing 40% of the agricultural area. In this rotation, the spring crop can be pea or sunflower. It was decided to prioritize lengthening rotation (1), as participants pointed out that pest pressure was more difficult to manage on this shorter rotation, which would benefit from being lengthened. For the “Sunflower” and “Hemp” scenarios, the lengthened rotation (1) becomes “rapeseed/wheat/wheat/additional crop/wheat”, whereas rotation (2) remains unchanged. For the “Alfalfa” scenario, a three-year implantation was considered. Given the important surface to be integrated, and in order not to unbalance the distribution of other crops, participants decided that half of the alfalfa area would be integrated before rotation (1), and the other half before rotation (2). Corresponding crop rotations and crop repartitions are available in Supplementary Materials (Appendix 5 and Appendix 6). For the “Alfalfa” scenario, alfalfa is assumed to be sold as fodder to livestock farmers.

4.2. Scenario evaluation

4.2.1. Impact on groundwater nitrate concentration trends

The co-constructed scenarios were simulated with the BICHE model to evaluate their impact in terms of nitrate concentration from 2018 to 2050, compared to a “business as usual” (BAU) scenario in which current crop patterns and technical practices would be maintained.

Simulation results highlight that current practices (BAU) are incompatible with reducing groundwater nitrate concentration below the 50 mg/l threshold in Pentvert (Figure 3). The BAU scenario leads to a concentration level of 86 mg/l on average in 2050. New scenarios of actions will be necessary to recover good groundwater quality in the Pentvert catchment in respect to nitrates.

However, none of the scenarios co-constructed by stakeholders make it possible to fall below the level of 50 mg/l by 2050 either (Figure 3, Table 2).

The scenario “N splitting” is the least effective, leading to an evolution of concentration that is very close to the BAU scenario. An explanation may be that the current splitting in 3 applications is already effective, one further application does not increase effectiveness substantially. Also, because of the structure of the BICHE model, the full potential of the scenario “N splitting” could not be evaluated. In practice, the further splitting of fertilizer application could enable farmers to better control total fertilization by adjusting the final dose applied to the needs of the crop, which could lead to a greater decrease in groundwater nitrate concentrations. However, this adjusting of the final dose could not be represented within the structure of the BICHE model, the total wheat fertilization dose remained unchanged, only its repartition during the year changed. The impact of the “N splitting” scenario may therefore be underestimated.

The “Hemp”, “Short cover” and “Sunflower” scenarios reduce groundwater nitrate concentration only to 82, 78 and 76 mg/l respectively by 2050. The impact of the “Short cover” scenario corresponds to a yield of 2 tDM/ha for the cover crop. This yield may be lower certain years when planting happens under bad conditions, e.g. when the end of summer and early fall are dry. Given the short duration of the intercrop period, the growth of the cover crop may be limited. Therefore, the evaluated effectiveness of the “Short cover” scenario may be on the optimistic side. Hemp and sunflower were considered promising by stakeholders because they require little fertilization (50 kg of N/ha). However, they also have limited needs (112 and 125 kg of N/ha, for yields of 7.5 tons of straw/ha and 2.7 ton/ha respectively). When they replace heavily fertilized but very demanding crops, the impact on groundwater nitrate concentration is moderate because the intake-export balance remains relatively average. Still, for a same implementation rate (+10% of agricultural surface, with identical changes to existing rotations) the “Sunflower” scenario is twice as efficient in decreasing concentration levels than the “Hemp” scenario.

Despite not being sufficient to reach the target level of 50 mg/l by 2050, the “Alfalfa” scenario stands out as the most effective in reducing Pentvert’s groundwater nitrate concentration, reaching 63 mg/l in 2050. Alfalfa generally does not require fertilization because it is able to fix inorganic nitrogen from the air on its own. However its needs may be high, depending on yield. This depends on plot management but it can also depend on the outlet sought. Yields of 10 tDM/ha, as modelled here, remain easily accessible. However, the share of nitrogen fixed by the nodules from the air compared to that coming from the soil remains difficult to quantify (Soltner, 2003), introducing some uncertainty in the estimated effectiveness of the measure.

The short term cycles that can be observed in concentration trends (Figure 3) are explained by the use of a repetition of meteorological series (years 2000-2009) to produce the forecast (Section 3.2). Years 2000 and 2001 were particularly wet, which explains the increase in concentration at the beginning of the cycles.

4.2.2. Cost for farmers

In terms of costs for farmers, two scenarios stand out (Table 3). On the one hand, implementing cover crops during short intercrop periods is by far the most expensive measure. Not only is it the most expensive in terms of unitary cost per hectare undergoing the change (113 €/ha/year), but it is also the scenario affecting the largest share of agricultural area (1742 ha), so its total cost is doubly high (197 k€/year for the total area). On the other hand, the “Hemp” scenario is the only one that produces an economic benefit instead of a cost (+27 €/ha/year on average, i.e. 33 k€/year for the total area).

For the “N splitting”, “Sunflower” and “Alfalfa” scenarios, average costs to farmers range between 22 and 51 € per hectare undergoing a change in agricultural practices. This hints at the order of magnitude of potential incentive measures to encourage farmers to adopt those practices (e.g. as part of agri-environmental contracts). In total, given the surfaces affected by the changes, average costs range between 29 and 44 k€ for the whole area, i.e. 2 to 4 % of the total agricultural semi-net margin of the area.

Results show a strong sensitivity of costs to crop prices variability, and a lesser sensitivity to yield variability (Figure 4). In a context of high crop prices, the cost will be larger than on average for all scenarios. Even the “Hemp” scenario will generate a cost instead of a benefit. The impact is even stronger for alfalfa as its price is stable: in a context of high

prices, the margin of alfalfa will not be higher than on average, while the margin of crops replaced by alfalfa could have been very high. In a context of low prices, the scenarios implemented can however limit economic losses. There is even a benefit for most crop rotation modification scenarios, except for the "Sunflower" scenario.

4.2.3. Additional exploratory scenarios

Given that none of the scenarios co-constructed by the stakeholders makes it possible to sustainably recover water quality compliant with EU directives threshold in respect to nitrates in Pentvert, the research team decided to simulate additional exploratory scenarios to better estimate the extent of changes in practices needed. First, given that the hydrogeological system exhibits significant inertia, a scenario in which all crops are replaced by grassland on 100 % of the agricultural area was considered ("Grass" scenario). The purpose of this theoretical scenario is to provide information on the inertia of the system in the absence of any supply of nitrates. In addition, three scenarios based on scenarios co-constructed by stakeholders but amplified with a doubled implementation rate were considered: "Sunflower x2" (reaching 30% of the agricultural area), "Hemp x2" (20%) and "Alfalfa x2" (40%).

Results show that in no instance will it be possible to recover groundwater nitrate concentrations below the 50 mg/l threshold by the 2027 WFD deadline (Figure 5 and Table 2). Even when completely stopping fertilizer application ("Grass" scenario), concentrations would only pass below the 50 mg/l threshold in 2031. The scenarios "Hemp x2" and "Sunflower x2" are still not sufficient to recover good groundwater quality in respect to nitrate by 2050. However, the "Alfalfa x2 scenario" makes it possible to pass below the 50 mg/l threshold by 2044.

Of the two exploratory scenarios that make it possible to decrease groundwater nitrates concentration below the threshold of 50 mg/l by 2050 ("Grass" and "Alfalfa x2"), the "Grass" scenario is the only one that generates a sharp decrease in nitrate concentration on the relative short-term (Figure 5). But the "Alfalfa x2" scenario is by far less costly (Table 3). For the "Grass" scenario, we assumed no potential for economic valorisation of the grass given the limited livestock farming outlet in the area. The total cost of the scenario therefore amounts to 100% of the semi-net agricultural margin in the Pentvert area, i.e. 1.2 M€/year. For the "Alfalfa x2" scenario, given the costs per hectare previously estimated and the number of hectares affected by a lengthening of rotations (Table 3), the total cost of this scenario is 81 k€/year on average, i.e. 7% of the total agricultural semi-net margin of the study area.

4.2.4. Cost-effectiveness

Figure 6 summarizes the impacts of the different scenarios in terms of cost-effectiveness. The criterion used to measure the effectiveness of the scenarios is the difference in groundwater nitrate concentration at the 2050 horizon compared to that of the "Business as usual" (BAU) scenario, in which current practices and rotations would be maintained. The "Hemp" scenario stands out as the most cost-effective, as it generates an overall benefit instead of a cost. However, its effectiveness is very limited so it is not a relevant measure to tackle the nitrates issue in Pentvert. The "Alfalfa x2" scenario proves both effective enough to pass the concentration reduction target and cost-effective. The Alfalfa scenarios are indeed the second most cost-effective scenarios overall. The "Grass" scenario appears over-effective (at the 2050 horizon) and the second least cost-effective scenario overall, after the "Short cover" scenario.

4.3. Discussion of evaluation results by stakeholders

Besides the evaluation of the effectiveness and cost of the scenarios, one of the additional technical and socioeconomic aspects (Table 4) considered as key by stakeholders was the need for outlets to be able to develop non-conventional crops (in this territory) such as Hemp or Alfalfa. Alfalfa can either be sold as fodder for local livestock farms or be processed into dehydrated alfalfa to reach a wider market, with a higher value-added. However, livestock farming is declining on the territory and would not provide a sufficient outlet for substantial surfaces of alfalfa as fodder, and there is no alfalfa dehydration facility in the vicinity.

Based on this, two options to sustainably recover good groundwater quality in the Pentvert drinking water catchment were presented by the research team during the final workshop and discussed with the stakeholders. A first option would be the implantation of alfalfa on a large-scale with the development of a dehydration industry on the territory. Large surfaces of alfalfa would be required for the dehydration sector to be economically viable, possibly engaging farms farther than the catchment protection area itself. This option was favoured by the stakeholders, as it would further the collective dynamic initiated in the territory to tackle the nitrate issue, maintain the agricultural fabric of the territory, and develop local employment. Implementing this option would first require a feasibility study and market research to ensure its economic viability. This is beyond the scope of this study.

If it was not possible to develop a dehydrated alfalfa sector, a second option would be to target the implantation of grass and alfalfa (with a fodder outlet) on plots where the vulnerability of the groundwater is the highest respective to nitrates. Minimizing the surfaces to be converted by targeting the most vulnerable plots would increase the cost-effectiveness of the measure. This action was not considered desirable by the stakeholders, as it would disrupt the collective dynamic initiated and was perceived as a decline for the territory. Implementing this option in the most cost-effective way would require a spatialized evaluation of the impacts on nitrate concentrations, to identify the plots where to implement the changes.

5. Discussion

5.1. A need for substantial changes in cropping systems to reach quality targets in the medium-long term

Scenario evaluation results in Pentvert confirm the importance of taking into account the long time when considering the impacts of agricultural measures on groundwater nitrate concentrations. Various studies in Europe have shown delays of 7 to 21 years in the effects of agricultural mitigation practices to improve groundwater quality (Bouraoui and Grizetti, 2014). Other studies have pointed up the difficulty of reaching the WFD quality target in groundwaters (Van Grinsven et al, 2016), and the need for substantial and expensive land management changes to achieve this target (Volk et al, 2008). In the Ems basin in Germany, losses in gross margin were estimated at 772 €/ha/year for a scenario replacing arable land with pasture (Volk et al, 2008), comparable to the “grass” scenario in Pentvert and its 498 €/ha/year loss in semi net margin. The case study of Pentvert is fairly representative: in Europe alone, its hydrogeological and agricultural contexts, with a predominance of field crops and a livestock sector in decline, are common in Northern France, Southern England, Netherlands, or Denmark for instance.

5.2. A simple lumped model adequate to explore scenarios of measures at the drinking water catchment scale

The BICHE model was used to evaluate the evolution of groundwater nitrate concentration trends at the drinking water catchment scale over time for different scenarios of agricultural practices. More complex discretized models have been used at the scale of groundwater well protection areas (Bonton et al, 2011). However, despite their complexity the performance of discretized models could be poor (Refsgaard and Hansen, 2010) and the use of complex models often has limitations when applied in an operational context (Perrin et al., 2001), whereas lumped models have been shown to successfully simulate nitrate concentration in groundwater wells (Hong et al, 2017; Woodward et al., 2017; Surdyk et al, 2021b). BICHE was selected for its ease of use and its relatively modest need of input data. Other lumped model are more refined than the BICHE model but the need for input data increases with the refinement (De Filippis et al., 2021).

The monthly time step and the simplifications inherent to lumped models are adapted to a certain extent to input data uncertainty (Surdyk et al. 2021b). For instance, agricultural data are difficult to obtain with precision (e.g. application dates) but the model uses monthly time steps so the dates do not need to be known with precision. These simplifications are not prohibitive since this lumped model aims to forecast global trends in nitrate concentration, not to describe nitrate concentration variations with precision for precise dates.

The aim of the approach developed is to provide a first ex-ante assessment via a relatively light and easily implemented process, to explore different scenarios of measures, identify suitable and unsuitable ones, and evaluate the appropriate order of magnitude for dimensioning relevant measures when dealing with groundwater. In that respect the use of the BICHE model is appropriate. Its only limitation was its inability to simulate fine-tuning fertilization practices. In the case of Pentvert however, this limitation did not result in being restrictive: since only major changes in cropping systems proved efficient enough to restore groundwater quality, we can assume that fine-tuning fertilization practices is not an efficient enough action anyway. Overall, the approach met its objectives of providing a first assessment. If necessary to proceed towards an implementation phase, complementary studies could be carried out in a second stage, to formulate a more precise action plan: extent and location of the actions, timing and evolution of actions over time, market research, etc.

5.3. A multi-disciplinary participatory approach that proved valuable to stakeholders

In terms of insight for stakeholders, the approach developed proved fruitful on several counts. First, it did respond to stakeholders' needs and provide them with valuable information. Participants indicated that "the approach had answered the questions they had at the beginning" of the participatory process. They also pointed out the "importance of providing information about economic and other aspects", such as outlets issues, and not only information about effectiveness, thereby validating the multidisciplinary nature of the approach. Second, the approach implemented enabled an objectivization of the issue. Some stakeholders' preconceptions were contradicted, others were validated: for some stakeholders, "the evaluation confirmed hands-on perceptions"; for others, they "had expected a stronger effectiveness from the "Hemp" scenario". The approach delivered cognitive impact (Hassenforder and Ferrand, 2021), and at the end of the process stakeholders had developed a shared vision of the issue (Rouillard et al, 2021): i) of the

inertia of the hydrosystem, ii) of the extent of changes required to sustainably recover good groundwater quality respective to nitrates, and iii) of potential courses of action for the territory.

5.4. On the use of cost-effectiveness analysis

Discussing the results of the cost-effectiveness analysis with the stakeholders involved in restoring the water quality of the catchment area validated the interest of the approach in informing decision-making, while also highlighting the limits of choosing measures based solely on optimising the cost-effectiveness ratio. Indeed, targeting the implantation of alfalfa in the most vulnerable sectors would make it possible to optimise the cost-efficiency ratios, but stakeholders pointed out that it would also constitute a significant risk of breaking the collective dynamic that has been in place for more than ten years in the drinking water catchment protection area, unlike the project to establish a dehydration sector. These results underline that the economic efficiency of the restoration actions cannot be the only criterion considered for the design of restoration programmes. Other economic, social and environmental criteria are also important to consider on the studied territories, and can lead to not selecting the most efficient actions from a cost-effectiveness point of view. These observations open up the prospect of coupling cost-effectiveness analyses with multi-criteria approaches, such as deliberative multi-criteria evaluations (Bryan and Kandulu, 2009; Munda, 2004; Pelenc and Etxano, 2020; Proctor and Drechsler, 2006; Straton et al., 2011).

5.5. Benefits of engaging stakeholders in scenario development and data collection

One key finding in the application of the approach to the Pentvert case study was that the scenarios of measures co-constructed and deemed achievable by the stakeholders were largely insufficient to recover good groundwater quality in respect to nitrates in the catchment. Measures that stakeholders expected promising proved insufficiently effective. This demonstrates the importance of carrying out such ex-ante evaluations, and of engaging stakeholders in the process: one benefit of the approach in Pentvert was to raise awareness on the inertia of the hydrosystem among stakeholders, and on the extent of the efforts required to reach nitrates concentration targets – efforts in terms of changes in agricultural practices and land use, and in terms of costs.

It however shows a limit to the approach of co-constructing scenarios of actions with stakeholders. As the co-constructed measures were far from being effective enough, their evaluation alone would not provide sufficient insight to inform local decision making. The research team had to propose and evaluate further exploratory scenarios to provide complementary information. These additional scenarios were useful in showing that major changes could enable to reach the desirable concentration target, confirming the value of scenarios proposed by the research team as a complement to co-constructed scenarios (Voinov and Brown Gaddis, 2008). However, they deviate from a strictly participatory approach, risking to weaken the stakeholders' engagement in the process if perceived unacceptable, and they remain exploratory and coarse scenarios.

As one feature of the approach was to keep the process light and easily implemented, and to avoid stakeholder fatigue (Reed, 2008), we organized only three stakeholders' workshops: one to co-construct scenarios, one to validate data and hypotheses needed for the evaluation of those scenarios, and a final one to discuss the evaluation results. There was a trade-off between i) taking time to involve stakeholders in the evaluation process via the data and hypothesis validation workshop, in order to include local knowledge and foster confidence in the evaluation results, at the risk of

not identifying effective enough scenarios among the co-constructed scenarios; and ii) not involving stakeholders in the evaluation process, in order to keep time to co-design a second series of improved scenarios, both effective and acceptable. We favoured the former, prioritizing stakeholders' confidence in the evaluation method and results (Bouraoui and Grizetti, 2014), and following the recommendation to combine scientific and local knowledge in participatory processes (Reed, 2008; Reed et al., 2013; Voinov and Brown Gaddis, 2008). Involving stakeholders in data collection enabled to obtain precise site-specific data that would not have been available otherwise (Voinov and Brown Gaddis, 2008), improving the accuracy of the evaluation.

Involving stakeholders in data collection and integration indeed proved beneficial, as they trusted the results of the evaluation even though some of them contradicted their a priori expectations. As they trusted the approach, participants also accepted the results of the additional exploratory scenarios formulated by the research team. During the final discussion workshop, stakeholders were able to use those results to further discuss possible ways ahead for the territory. Those are crucial elements to move beyond scenario development and facilitate the development of an effective policy (Reed et al., 2013), supported by stakeholders – in particular when their a priori expectations are not met.

A perspective to improve the approach would be to make the multidisciplinary evaluation tools more automated, to be able to use them directly with stakeholders in quasi real-time in an interactive process during a participatory workshop (Chantre et al, 2016). This would make it possible to further explore and refine measures that would be both effective in terms of reducing groundwater nitrate concentrations and acceptable to the stakeholders. In that respect, the use of a simple model as BICHE, with low data and computational requirements, is particularly practical.

5.6. Transferability of the approach

The strength of the approach is to provide useful insight to stakeholders into the costs and time required for groundwater quality restoration, at the drinking water catchment scale, for which useful and easily applicable tools are needed. The results of the application to the Pentvert catchment, although representative of similar sites throughout Europe, are not directly transferable to other territories. However, the approach itself is entirely transferable to other sites, whatever their hydrogeological context, types of agricultural pressures, and their evolution over time.

One limit to the implementation of the approach may be that it requires privileged local conditions: a good prior knowledge of groundwater quality and agricultural practices, as well as the involvement of local stakeholders. As to evaluating the effectiveness of restoration measures, sufficiently long time series are needed for the calibration of hydrogeological models. However, using the lumped model BICHE decreases input data requirements, while enabling to evaluate impacts on groundwater nitrate concentration. Overall, the BICHE model has proven easy to implement (Surdyk et al., 2021b). As to evaluating the costs of the measures, the participatory data collection approach has proven fruitful and is easily replicable.

6. Conclusion

The approach developed made it possible to co-construct scenarios of actions with local stakeholders and evaluate both their effectiveness on groundwater nitrate concentrations and their cost, allowing to identify the most cost-effective measures. Groundwater quality modelling showed the inertia of the local hydrosystem and demonstrated to stakeholders that improvement can only be expected in the medium to long term. Besides, it demonstrated that greater changes in cropping patterns than initially imagined by stakeholders are needed to reach the target of 50 mg/l. The discussion of results by stakeholders made it possible to identify possible ways forward to take up the most cost-effective measures and to improve their economic outcome.

Results demonstrate once again the need to take into account the long time when looking at the effects of agricultural practices on groundwater quality, and the importance of such ex-ante evaluation in face of the inertia of hydrosystems. The approach developed has been shown to provide valued and trusted information to stakeholders and to objectify debates. Stakeholders have shown interest in the evaluation of costs and in qualitative technical and socio-economic information, in addition to the evaluation of the effectiveness of measures, validating the multidisciplinary dimension of the approach. The uptake of effective actions on a territory will be contingent on their potential socio-economic and technical drawbacks, in the local context.

We advocate engaging stakeholders when contemplating scenarios of agricultural practices for a durable reduction in groundwater nitrate concentration at the catchment scale, especially in catchments where top-down prescriptive measures have proven inadequate. The proposed measures will be relevant in the local context and for the stakeholders. As a result, the approach will provide useful information, this information will be accepted with confidence, and stakeholders will be able to use it. This is decisive to move towards the implementation of measures that are both efficient to tackle the nitrates issue at the local scale and embraced by the different stakeholders.

The proposed approach has the advantage of being easy to implement, requiring relatively little data compared to other modeling approaches, and is therefore easily applicable to other drinking water catchments where needed. It fills the need for a useful and easily applicable methodology to identify the best actions to implement at this local scale. Since the lack of visibility on the extent and costs of the efforts required and on their impacts can be an important obstacle to adopting new actions and practices, we recommend that this type of approach be implemented as often as possible to support the identification and adoption of effective restoration measures. This applies especially to drinking water catchments where no previous study has been carried out and a first assessment is needed, or where previous efforts have remained unsuccessful. Besides, the implementation of the approach to several pilot cases representative of the diversity of agro-hydrogeological contexts would provide reference studies that could be extrapolated to other similar sites, and contribute to improving the design and dimensioning of groundwater quality restoration programs.

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References

Agreste, 2018. - Online data - Available at <https://agreste.agriculture.gouv.fr/agreste-web/disaron/!searchurl/searchUiid/search/>

Alcon, F., de-Miguel, M.D., Martínez-Paz, J.M., 2020. Assessment of real and perceived cost-effectiveness to inform agricultural diffuse pollution mitigation policies. *Land Use Policy* 104561. <https://doi.org/10.1016/j.landusepol.2020.104561>

Balana, B.B., Vinten, A., Slee, B., 2011. A review on cost-effectiveness analysis of agri-environmental measures related to the EU WFD: Key issues, methods, and applications. *Ecological Economics* 70, 1021–1031. <https://doi.org/10.1016/j.ecolecon.2010.12.020>

Baran N., Surdyk N., Auterives C., 2021. Pesticides in groundwater at a national scale (France): Impact of regulations, molecular properties, uses, hydrogeology and climatic conditions. *Science of the Total Environment*. Volume 791, 15 October 2021, 148137, <https://doi.org/10.1016/j.scitotenv.2021.148137>

Belmans, E., Campling, P., Dupon, E., Joris, I., Kerselaers, E., Lammens, S., Messely, L., Pauwelyn, E., Seuntjens, P., Wauters, E., 2018. Chapter Two - The Multiactor Approach Enabling Engagement of Actors in Sustainable Use of Chemicals in Agriculture, in: Capri, E., Alix, A. (Eds.), *Advances in Chemical Pollution, Environmental Management and Protection*. Elsevier, pp. 23–62. <https://doi.org/10.1016/bs.apmp.2018.03.001>

Berbel J., Martin-Ortega J., Mesa P., 2011. A cost-effectiveness analysis of water-saving measures for the Water Framework Directive: the case of Guadalquivir River Basin in Southern Spain. *Water Resources Management* 25: 623-640.

Bommelaer O. and Devaux J., 2011. Assessing water pollution costs of farming in France. Department of the Commissioner General for Sustainable Development, Studies & documents n°52EV.

Bonton, A., Rouleau, A., Bouchard, C., Rodriguez, M.J., 2011. Nitrate transport modeling to evaluate source water protection scenarios for a municipal well in an agricultural area. *Agricultural systems*, 104 (5) 429-439

Bouraoui, F. and Grizetti, B., 2014. Modelling mitigation options to reduce diffuse nitrogen water pollution from agriculture. *Science of the Total Environment* 468-469. <http://dx.doi.org/10.1016/j.scitotenv.2013.07.066>

Bryan B.A. et Kandulu J.M., 2009. Cost-effective alternatives for mitigating *Cryptosporidium* risk in drinking water and enhancing ecosystem services, *Water Resources Research*, vol. 45, n°8, pp. W08437.

Chambre d'Agriculture de la Sarthe, 2018. Mes itinéraires marges 2017-2018.

Chambre d'Agriculture de la Mayenne, 2016. Synthèse des marges cultures 2015-2016.

Chantre, E., Guichard, L., Ballot, R., Jacquet, F., Jeuffroy, M-H., Prigent, C., Barzman, M., 2016. Co-click'eau, a participatory method for land-use scenarios in water catchments. *Land Use Policy* 59: 260-271. [10.1016/j.landusepol.2016.09.001](https://doi.org/10.1016/j.landusepol.2016.09.001)

COMIFER, 2013. Calcul de la fertilisation azotée - Guide méthodologique pour l'établissement des prescriptions locales - Cultures annuelles et prairies. COMIFER, 91 p.

De Filippis, G., Ercoli, L., Rossetto, R., 2021. A Spatially Distributed, Physically-Based Modeling Approach for Estimating Agricultural Nitrate Leaching to Groundwater. *Hydrology* 8(1), 8. <https://doi.org/10.3390/hydrology8010008>

Davies, A. R., Doyle, R. and Pape, J., 2012. Future visioning for sustainable household practices: spaces for sustainability learning? *Area* Vol. 44 No. 1, pp. 54–60. doi: 10.1111/j.1475-4762.2011.01054.x

- Essien, E.E., Said Abasse, K., Côté, A., Mohamed, K.S., Baig, M.M.F.A., Habib, M., Naveed, M., Yu, X., Xie, W., Jinfang, S., Abbas, M., 2022. Drinking-water nitrate and cancer risk: A systematic review and meta-analysis. *Archives of environmental & occupational health* 77, 51–67. <https://doi.org/10.1080/19338244.2020.1842313>
- EurEau, 2021. Europe's Water in Figures. An overview of the European drinking water and waste water sectors. 2021 Edition. ISBN 978-2-9602226-3-0
- Feuillette S., Levrel H., Boeuf B., Blanquart S., Gorin O., Monaco G., Penisson B., Robichon S., 2016. The use of cost-benefit analysis in environmental policies: some issues raised by the Water Framework Directive implementation in France. *Environmental Science and Policy* 57: 79-85
- Foster, S. and Chilton J., 2021. Policy experience with groundwater protection from diffuse pollution – a review. *Current Opinion in Environmental Science & Health* 23:100288
- Graveline, N., Rinaudo, J., 2007. Constructing scenarios of agricultural diffuse pollution using an integrated hydro-economic modelling approach. *Eur. Water* 17, 18.
- Guppy, L., Uyttendaele, P., Villholth, K.G., Smakhtin, V., 2018. Groundwater and Sustainable Development Goals: Analysis of Interlinkages. UNU-INWEH Report Series, Issue 04, United Nations University Institute for Water, Environment and Health, Hamilton, ON, Canada
- Hassenforder, E., Ferrand, N., 2021. Évaluer une démarche participative. In : Des démarches participatives pour penser ensemble la gestion de l'eau et des territoires. *Sciences Eaux et Territoires* n°35.
- Hérivaux C., Gauthey J., 2018. Les bénéfices liés à la protection des eaux souterraines : pourquoi et comment leur donner une valeur monétaire ? Agence française pour la biodiversité. Collection Comprendre pour agir (31). 72 pages.
- Hérivaux C., Gourcy L., Cadilhac L., 2014. Restaurer le bon état à l'échelle d'une masse d'eau souterraine affectée par les pollutions diffuses d'origine agricole : où et comment agir au moindre coût ? Hors-Série n°14. *Sciences Eaux & Territoires*. <https://doi.org/10.14758/SET-REVUE.2014.HS.01>
- Hérivaux C., Orban P., Brouyère S., 2013. Is it worth protecting groundwater from diffuse pollution with agricultural environmental schemes? A hydro-economic modeling approach, *Journal of Environmental Management*. <https://doi.org/10.1016/j.jenvman.2013.04.058>
- Hong, N., Hama, T., Suenaga, Y., Huang, X., Ito, H., Kawagoshi, Y., 2017. Simplified Lumped Groundwater Model to simulate Nitrate Concentration Dynamics. *J. Hydrol. Eng.* 22(10): 04017043. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001564](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001564).
- Korfmaier, K., 2001. The Politics of participation in watershed modeling. *Environmental Management* 27, 161–176. <https://doi.org/10.1007/s002670010141>
- Ledoux, E., Gomez, E., Monget, J.M., Viavattene, C., Viennot, P., Ducharne, A., Benoit, M., Mignolet, C., Schott, C., Mary, B., 2007. Agriculture and groundwater nitrate contamination in the Seine basin. The STICSeMODCOU modelling chain. *Sci. Total Environ.* 375, 33e47. <http://dx.doi.org/10.1016/j.scitotenv.2006.12.002>
- Martin-Ortega J., 2012. Economic prescriptions and policy applications in the implementation of the European Water Framework Directive. *Environmental science and policy* 24: 83-91.
- Meals, D.W., Dressing, S.A., Davenport, T.E., 2010. Lag time in water quality response to best management practices: a review. *Journal of Environmental Quality* 39(1):85–96. <https://doi.org/10.2134/jeq2009.0108>
- Munda G., 2004. Social multi-criteria evaluation: Methodological foundations and operational consequences, *European Journal of Operational Research*, vol. 158, n°3, pp. 662-677.
- Pelenc J. and Etxano I., 2020. Capabilities, Ecosystem Services, and Strong Sustainability through SMCE: The Case of Haren (Belgium), *Ecological Economics*, vol. 182, October 2020.

- Peña-Haro, S., Llopis-Albert, C., Pulido-Velazquez, M., Pulido-Velazquez, D., 2010. Fertilizer standards for controlling groundwater nitrate pollution from agriculture: El Salobral-Los Llanos case study, Spain. *J. Hydrol.* 392, 174e187. <http://dx.doi.org/10.1016/j.jhydrol.2010.08.006>.
- Peña-Haro, S., Pulido-Velazquez, M., Sahuquillo, A., 2009. A hydro-economic modelling framework for optimal management of groundwater nitrate pollution from agriculture. *J. Hydrol.* 373, 193e203. <http://dx.doi.org/10.1016/j.jhydrol.2009.04.024>.
- Perrin, C., Michel, C., Andréassian, V., 2001. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. *J. Hydrol.* 242, 275-301
- Proctor W. and Drechsler M., 2006. Deliberative multicriteria evaluation, *Environment and Planning C: Government and Policy*, vol. 24, n°2, pp. 169-190.
- Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. *Biol. Conserv.*, 141 (2008), pp. 2417-2431, 10.1016/j.biocon.2008.07.014
- Reed, M. S., Kenter, J., Bonn, A., Broad, K., Burt, T. P., Fazey, I. R., Fraser, E.D.G., Hubacek, K., Nainggolan, D., Quinn, C.H., Stringer, L.C. & Ravera, F., 2013. Participatory scenario development for environmental management: A methodological framework illustrated with experience from the UK uplands. *Journal of environmental management*, 128, 345-362.
- Refsgaard, J.C., Hansen, J.R., 2010. A good-looking catchment can turn into a modeller's nightmare. *Hydrol Sci J.* 55(6), 899-912
- Rouillard, J., Neverre, N., Rinaudo, J-D., 2021. Initiating collective action for the management of deep confined aquifer systems: application of a participatory scenario approach in France. *Hydrogeology Journal*. <https://doi.org/10.1007/s10040-021-02420-1>
- Sohier C., Degré A., 2010. Modelling the effects of the current policy measures in agriculture: an unique model from field do regional scale in Walloon region of Belgium. *Environmental Science and Policy* 13: 754-765.
- Soltner, D., 2003. Les bases de la production végétale Tome1 Le sol et son amélioration - 23ème édition. Collection Sciences et techniques agricoles – Sainte-Gemmes-sur-Loire. 467p.
- Straton A.T., Jackson S., Marinoni O., Proctor W. and Woodward E., 2011. « Exploring and evaluating scenarios for a river catchment in Northern Australia using scenario development, multi-criteria analysis and a deliberative process as a tool for water planning. », *Water resources management*, vol. 25, n°1, pp. 141-164.
- Surdyk, N.; Gutierrez, A. ; Thiery, D. (2020) - Transfert de nitrates à l'échelle du bassin d'alimentation de captages d'eau souterraine du bassin Loire-Bretagne : actualisation des modélisations et essais de simplification. BRGM/RP-69118-FR, 153 p. <http://infoterre.brgm.fr/rapports//RP-69118-FR.pdf>
- Surdyk N., Gourcy L., Bault V., Baran N., 2021a. Study of nitrate transport in the chalk vadose zone in catchment areas in Picardy (France). *Geological Society, London, Special Publications*, 517, <https://doi.org/10.1144/SP517-2020-164>
- Surdyk N., Gutierrez A., Baran N., Thiéry D., 2021b. A lumped model to simulate nitrate concentration evolution in groundwater at catchment scale. *Journal of hydrology*. <https://doi.org/10.1016/j.jhydrol.2020.125696>
- Thiéry, D. and Seguin, J.-J., 1985. Modélisation globale des transferts de nitrates dans un bassin hydrogéologique pour prévoir l'évolution des concentrations dans les eaux souterraines. Description du modèle BICHE. Rapport BRGM 85 SGN 663 EAU, 182 p. Available at : <http://infoterre.brgm.fr/rapports//85-SGN-663-EAU.pdf>
- Tzilivakis, J., Green, A., Warner, D.J and Lewis, K.A., 2020. Identification of approaches and measures in action programmes under Directive 91/676/EEC. Final report: Report prepared for Directorate-General Environment, European Commission, for project ENV.D.1/SER/2018/0017 by the Agriculture and Environment Research Unit (AERU), University of Hertfordshire, United Kingdom.

Valé, M., 2006. Quantification et prédiction de la minéralisation nette de l'azote du sol in situ, sous divers pédoclimats et systèmes de culture français. Thèse, INPT-ENSAT, 183 pp.

Van Grinsven, H.J.M., Tiktaka, A., Rougoor, C.W., 2016. Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. *NJAS - Wageningen Journal of Life Sciences* 78: 69–84

Viavattene, C., 2006. Exploitation socio-économique de la modélisation souterraine du transfert des nitrates à l'échelle du bassin de la Seine.

Voinov A., Brown Gaddis E.J., 2008. Lessons for successful participatory watershed modeling: a perspective from modeling practitioners. *Ecol Model*, 216 (2) (2008), pp. 197-207, 10.1016/j.ecolmodel.2008.03.010

Volk, M., Hirschfeldb, J., Dehnhardtc, A., Schmidtd, G., Bohna, C., Lierscha, S., Gassmane, P. W., 2008. Integrated ecological-economic modelling of water pollution abatement management options in the Upper Ems River Basin. *Ecological Economics* 66: 66-76. 10.1016/j.ecolecon.2008.01.016

Ward, M.H., Jones, R.R., Brender, J.D., de Kok, T.M., Weyer, P.J., Nolan, B.T., Villanueva, C.M., van Breda, S.G., 2018. Drinking Water Nitrate and Human Health: An Updated Review. *Int J Environ Res Public Health* 15, 1557. <https://doi.org/10.3390/ijerph15071557>

Wiering, M., Boezeman, D., and Crabbé, A., 2020. The Water Framework Directive and Agricultural Diffuse Pollution: Fighting a Running Battle? *Water* 12-1447. doi:10.3390/w12051447

Woodward, S.J.R., Wohling, T., Rode, M., Stenger, R., 2017. Predicting nitrate discharge dynamics in mesoscale catchments using the lumped StreamGEM model and Bayesian parameter inference. *Journal of Hydrology* 552: 684:703.

Figures and tables

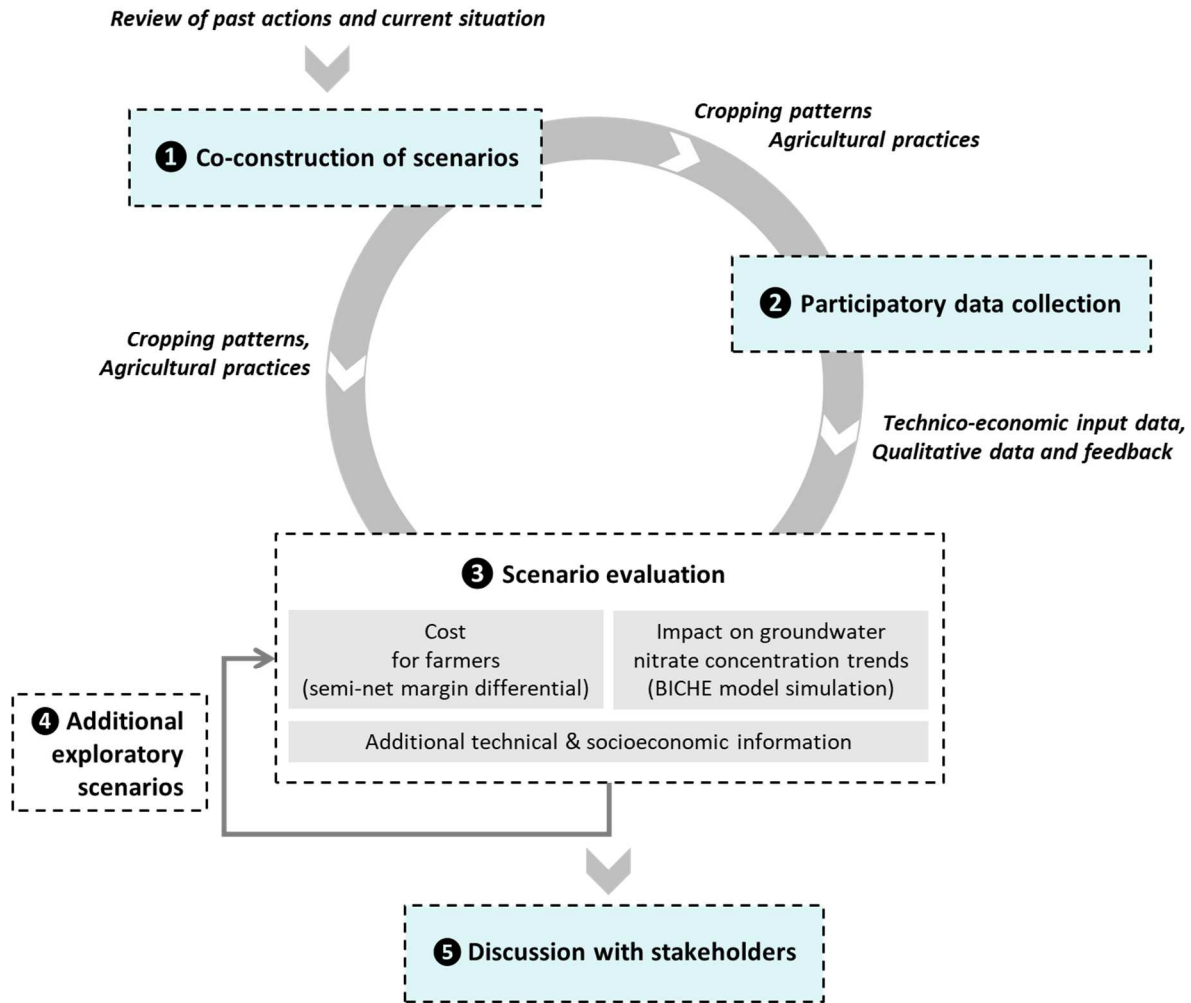


Figure 1: Overview of the methodology (participatory stages involving local stakeholders are highlighted in blue)

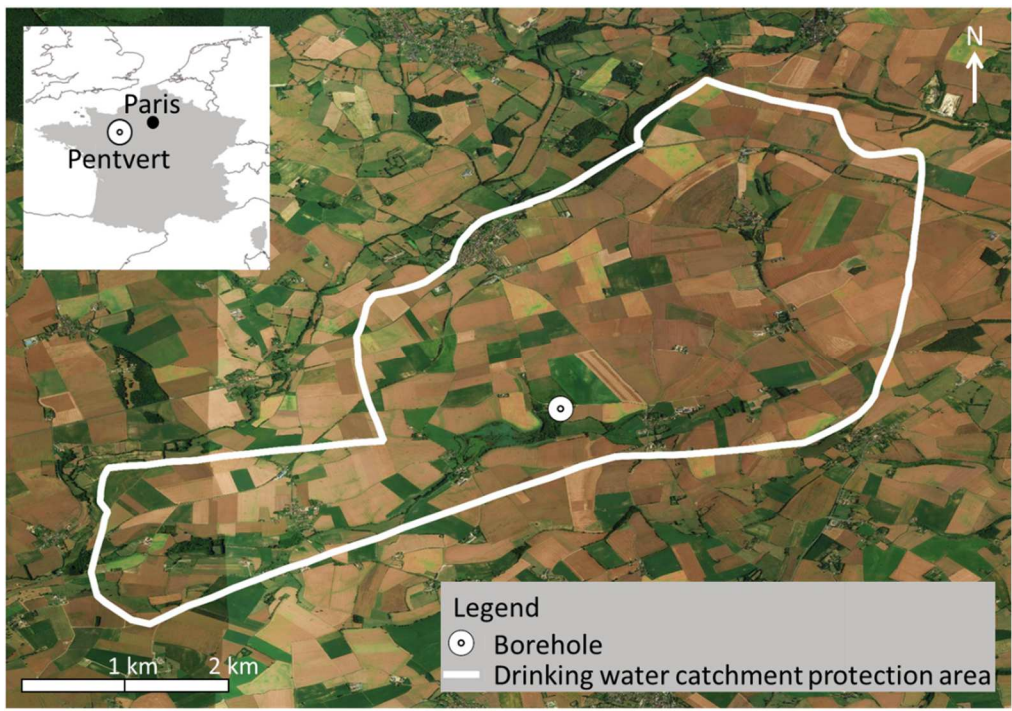


Figure 2: The drinking water catchment of Pentvert (France)

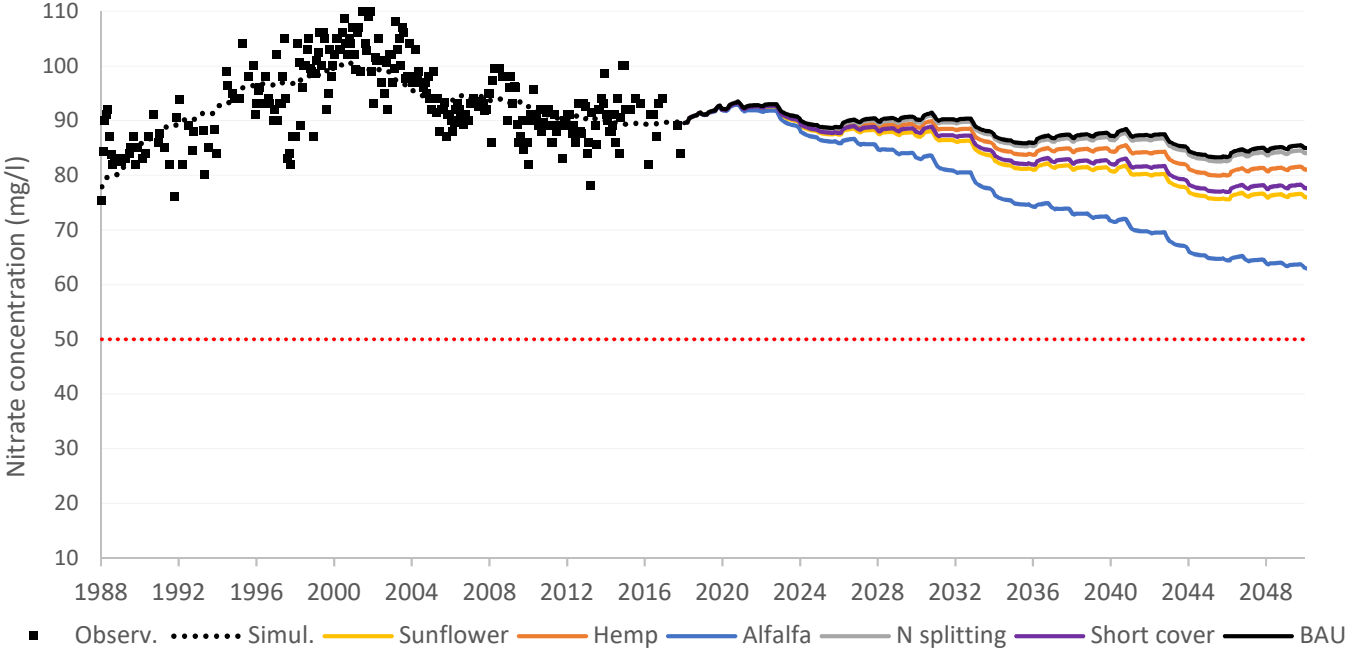


Figure 3 : Projection of nitrate concentration trends for the different scenarios designed by the stakeholders, compared to the target level of 50mg/l. (Observ. = observed; simul. = simulated for calibration)

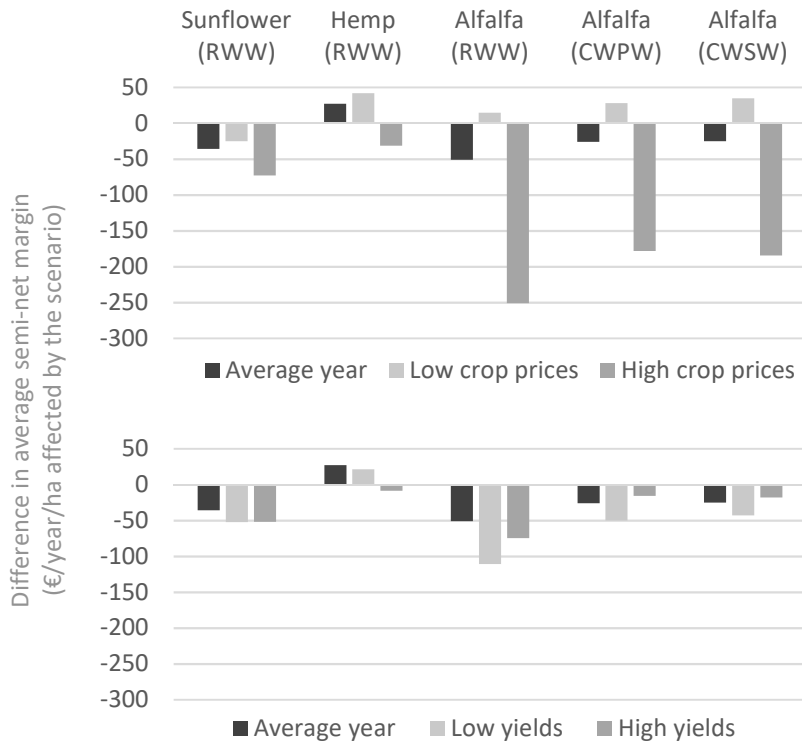


Figure 4: Difference in average semi-net margin between the initial rotation and the lengthened rotation for the different scenarios, in different crop yields and prices contexts. Initial crop rotation is indicated between brackets (RWW: Rape/Wheat/Wheat; CWPW: Corn/Wheat/Pea/Wheat; CWSW: Corn/Wheat/Sunflower/Wheat).

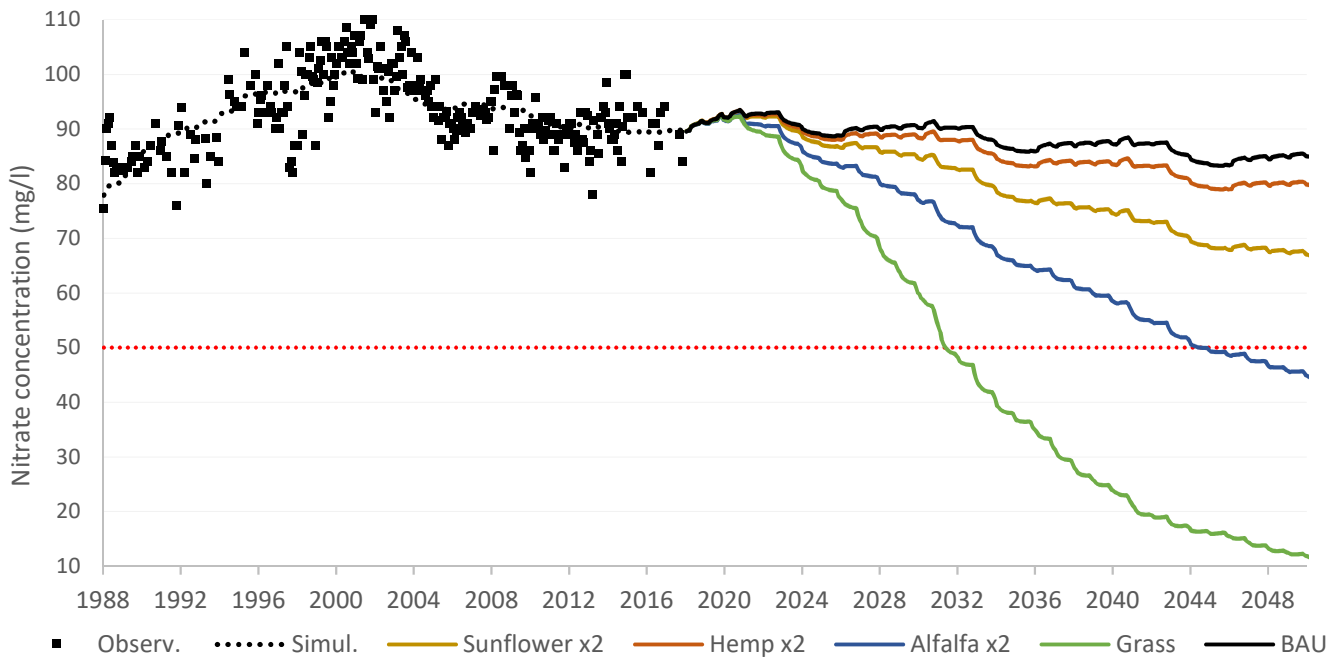


Figure 5: Projection of nitrate concentration trends for the additional exploratory scenarios, compared to the target level of 50mg/l. (Observ. = observed; simul. = simulated for calibration)

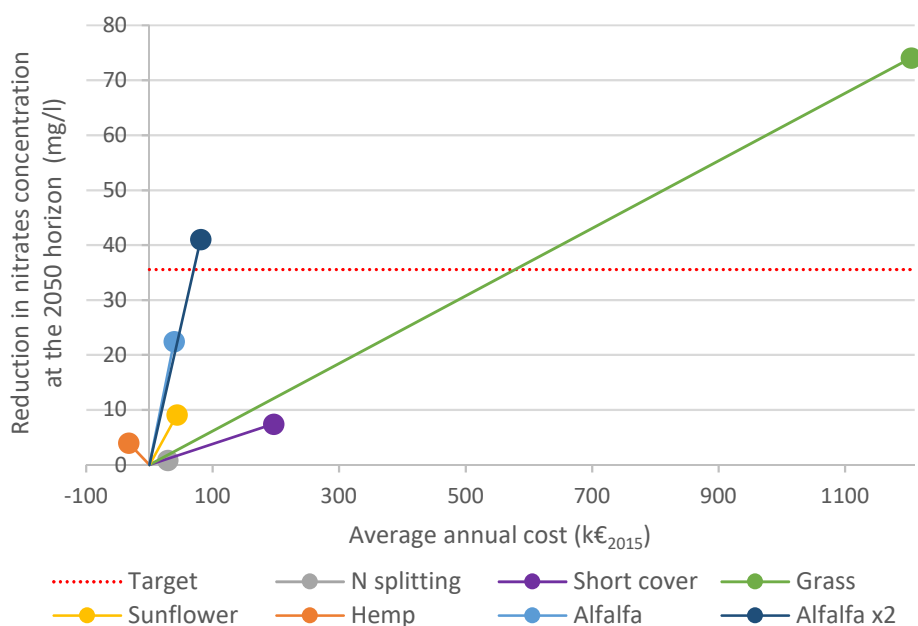


Figure 6: Cost-effectiveness of the different scenarios at the 2050 horizon

Table 1: Co-constructed scenarios

Scenario	Rationale	Implementation rate
N splitting	Distributing the application when the crop is better able to use the nutrient may increase N efficiency.	All wheat area – 1 additional application
Short cover	A cover crop with rapid development and strong nitrate absorption capacity is sown after harvesting the main crop and destroyed before planting the next crop. It absorbs some of the nitrogen and then releases it when crops need it most. Nitrogen is immobilized during months when the rains can be heavy.	All short intercropping periods
Sunflower	Sunflower requires low fertilization compared to other crops.	+10% of agricultural area
Hemp	Hemp requires low fertilization compared to other crops.	10% of agricultural area
Alfalfa	Alfalfa requires little, if any, fertilization. In addition, it is a multi-year crop, which limits fertilization for several consecutive years.	20% of agricultural area

Table 2: Impact of scenarios on groundwater nitrate concentration levels at the 2050 horizon

	BAU	Co-constructed scenarios					Additional exploratory scenarios			
		N splitting	Short cover	Hemp	Sunflower	Alfalfa	Hemp *2	Sunflower *2	Alfalfa *2	Grass
Average [N] in 2050 (mg/l)	86	85	78	82	76	63	80	67	45	11
Passing below the threshold of 50 mg/l	no	no	no	no	no	no	no	no	in 2044	in 2031

Table 3: Cost of scenarios for farmers

	Co-constructed scenarios					Additional exploratory scenarios	
	N splitting	Short cover	Hemp	Sunflower	Alfalfa	Alfalfa x2	Grass
Average semi-net margin of initial rotation (€/ha/year)	-	-	557	557	513 to 557	513 to 557	-
Average semi-net margin of lengthened rotation (€/ha/year)	-	-	584	521	488 to 506	488 to 506	-
Average unitary cost (€/ha affected/year)	22	113	-27	36	25 to 51	25 to 51	498

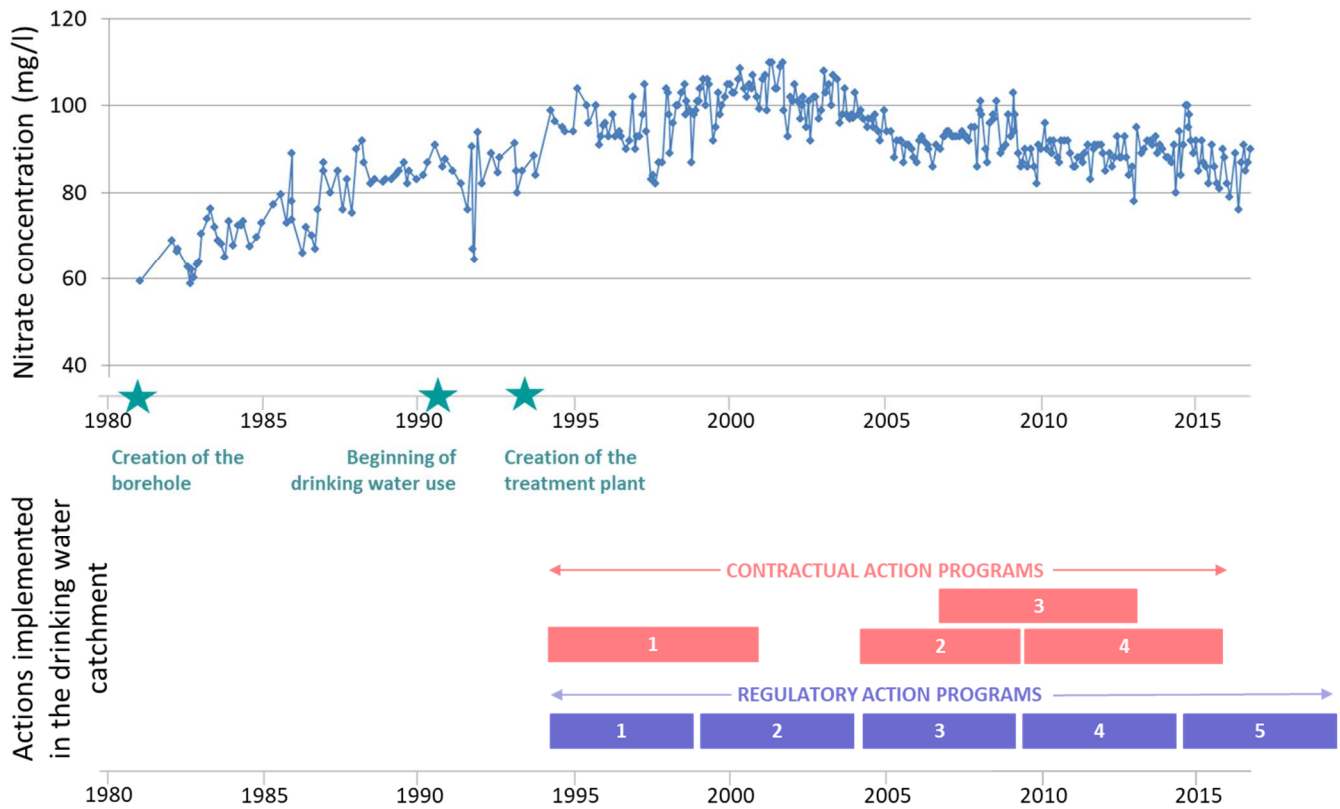
Area affected (ha)	1328	1742	1210	1210	1048	2073	2419
Total cost (k€/year)	29	197	-33	44	39	81	1205
Total cost (% of current average total annual margin)	2%	16%	-3%	4%	3%	7%	100%

Table 4: Additional technical and socioeconomic aspects in evaluating the scenarios

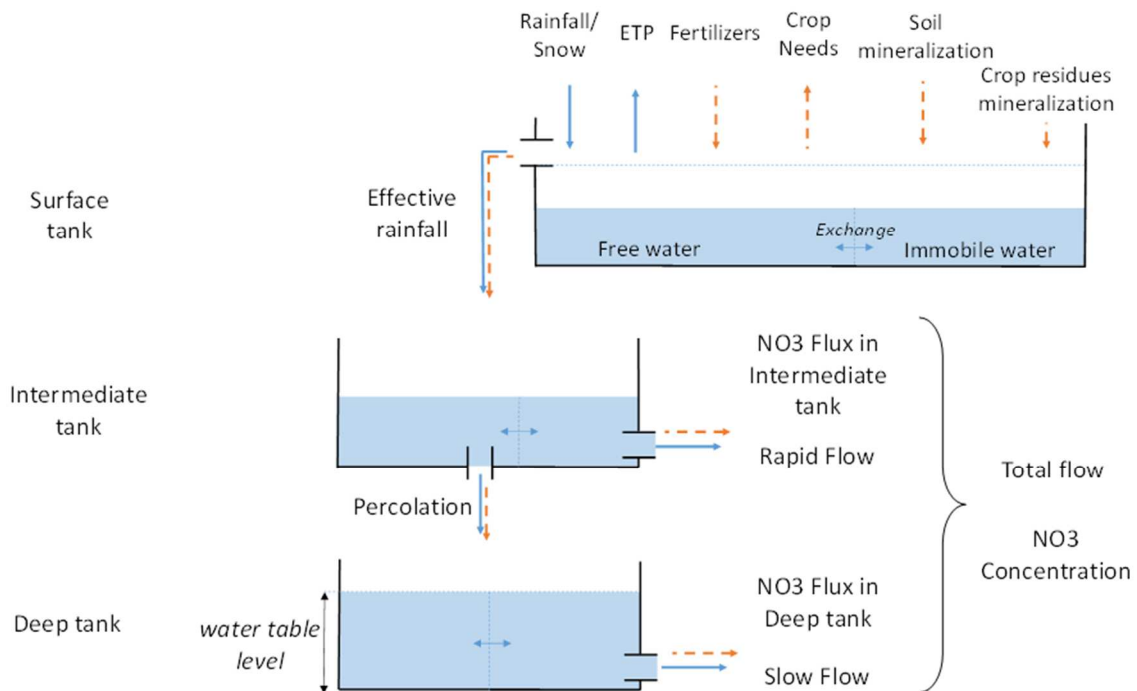
Scenario	Positive aspects	Negative aspects
N splitting	Impact of split-application on the yield and protein level of the crop.	
Short cover	Potential savings for the following crop: less nitrogen, phytosanitary products and tillage.	
Sunflower	Susceptible to pests.	
Hemp	Zero phytosanitary product. Good precedent crop for wheat (higher yield).	Requires a commercialization contract and local outlet. Requires significant storage capacities, which may be difficult for cattle breeders already storing straw. Harvest is complicated; managing working time is difficult especially for breeders (harvest during calving time). Requires a seed dryer.
Alfalfa	Good precedent for other crops, in terms of yield gains, nitrogen savings, reduction of sanitary risks.	High equipment costs for harvesting. Requires outlets: livestock farms for selling as fodder, or dehydration plant.

Supplementary materials

Appendix 1: Past evolution of groundwater nitrate concentration and restoration measures in the Pentvert catchment



Appendix 2: Diagram of the BICHE model



Appendix 3: Semi-net margins of the different crops (€/ha), on average and in high and low yield and prices contexts

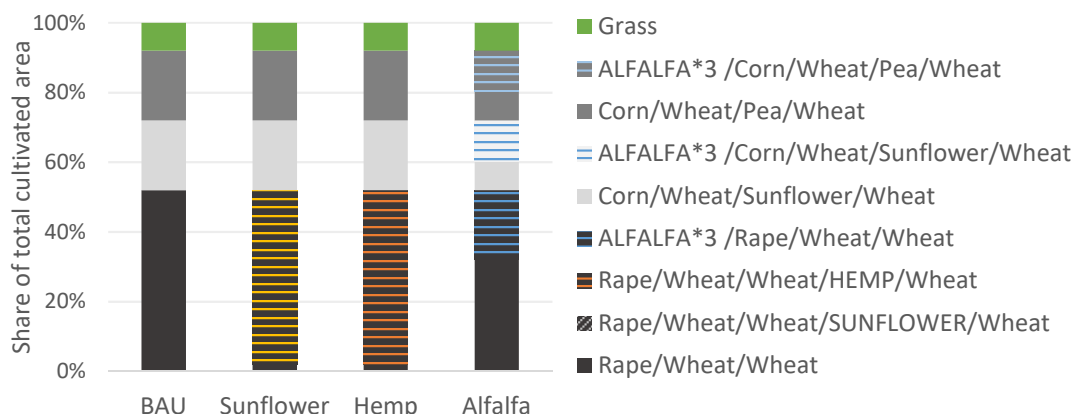
Wheat	Rapeseed	Corn (grain)	Pea	Sunflower	Alfalfa (fodder)	Hemp
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Average	514	643	607	430	420	455	736
High prices	922	1027	1073	566	628	455	836
Low prices	400	477	369	388	325	455	661
High yield	704	815	607	496	518	592	736
Low yield	475	539	295	321	256	275	624

Appendix 4: Additional charges reducing agricultural margins for scenarios of changes in fertilization and intercropping practices

	N splitting	Short cover
Additional charges	Additional application of mineral nitrogen (equipment, fuel, labour), associated monitoring (additional nitrogen dosage).	Planting costs (seeds, equipment, fuel, labour), destruction costs (equipment, fuel, labour), potential phytosanitary product.
Cost (€/ha/year)	22	113

Appendix 5: Crop rotations in the different scenarios



Appendix 6: Crop repartition in the different scenarios

