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DG Environment

Economic assessment of groundwater protection

A sensitivity analysis of costs-benefits results illustrated by a small aquifer protection in North Jutland, Denmark

Case study report No. 3

A project financed by the European Commission

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Sébastien LOUBIER

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Abstract

The field site under study consists of a small aquifer in the North Jutland Region of Denmark.

This aquifer is characterised by increasing nitrate content. In order to prevent deterioration of the water quality and to respect the European norms for drinking water (nitrate content < 50mg/l), the local government decided in 1997 to protect that aquifer and to restore its quality. The project is named “Drastrup” and consists of limiting nitrogen discharge due to agricultural activity. The total area concerned is the aquifer recharge area, in other words, one thousand hectares : 90% intensive agriculture and 10% residential zone in the city of Frejlev.

The main objectives of the project were to ensure that groundwater quality would comply with European drinking water standards and avoid the need to implement the costly treatment measures that would have been necessary if the groundwater protection measures had not been taken. The main way to reach this objective was to turn a zone of intensive agriculture into 500 hectares of forestlands and 400 hectares of grasslands.

A costs-benefits analysis of the Drastrup project already exists. Considering that analysis as a departure point, the objective of the present case study is to assess the variation in benefits to society induced by several parameter changes.

We then constructed a simplified integrated model to simulate various costs benefits analysis results that could be obtained by modifying economic or physical parameters.

The results of the real Drastrup project are presented and reveal that it would definitely be necessary to treat water before supplying it, but also that the net social benefit of the project is largely positive (near 10 million €). We also emphasise that a delay in implementation would inevitably lead to a reduction of the benefits and conclude that the Drastrup project does not need any financial incentive or statutory constraints, since financial compensation can be made between agents suffering a loss of revenue, and the others.

However, the Drastrup project has the particularity of generating very high recreational benefits due to the forest in question, and these benefits are essentially due to its proximity to a residential area. We then emphasise that the level of potential leisure benefits largely influences the costs-benefits analysis results.

Other sensitivity analyses are then made to simulate higher agricultural incomes, higher present-time preferences and different transfer time of water between the surface and the aquifer.

We then conclude that it seems impossible to generalise any case study since the same aquifer characteristics can lead to different results depending on economic as well as physical parameters, and for given economic characteristics.

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Introduction

The field site under study consisted of a small sandy aquifer in the North Jutland Region of Denmark (Figure 1).

This aquifer is affected by pesticides and nitrate diffuse pollution from agricultural and household gardens. Its recharge area is approximately 1000 ha and the annual potential withdrawal is 2.8 million m^3. Only 2.2 million m^3 are currently being withdrawn and contribute one third of Aalborg's drinking water needs.

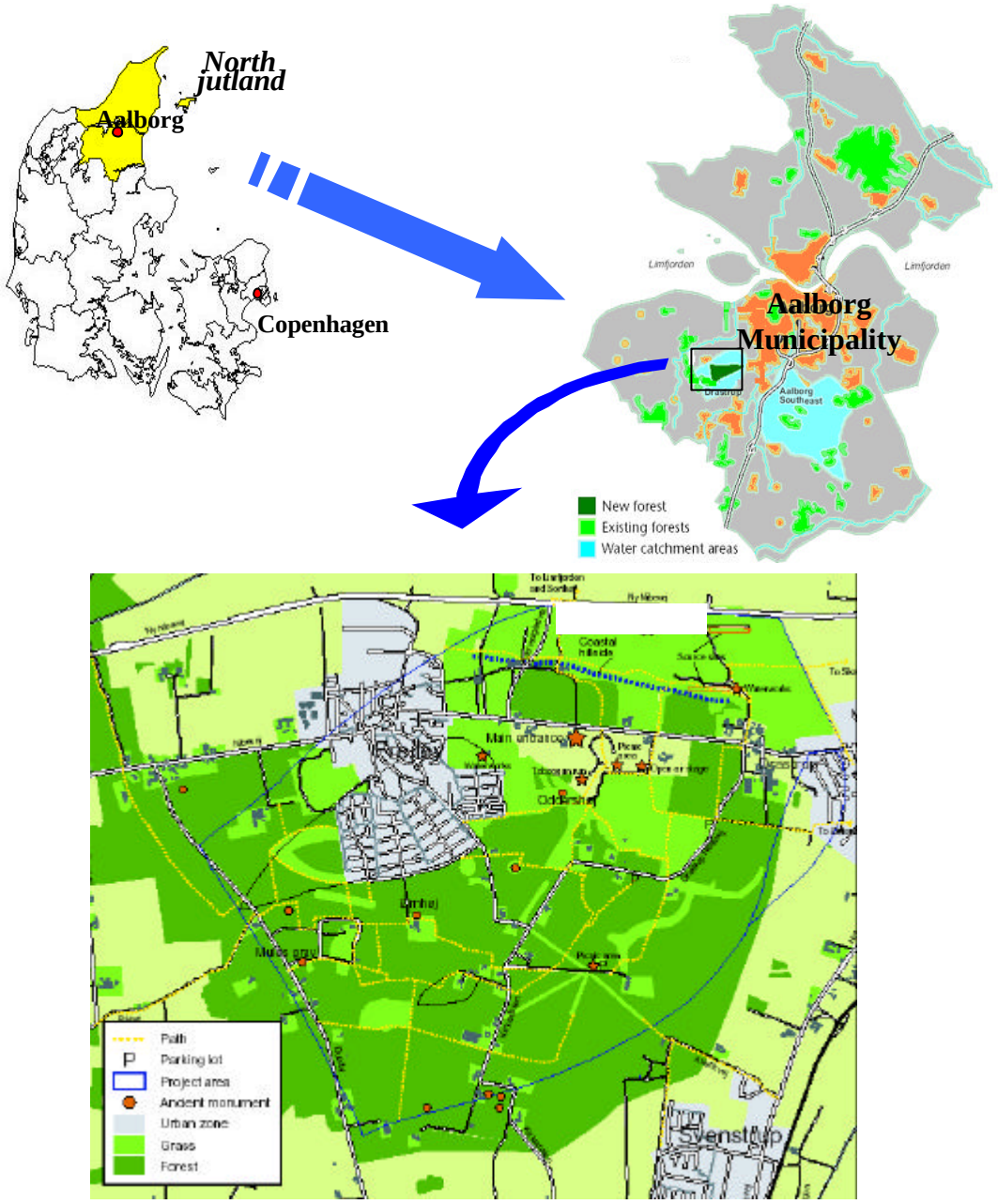

Figure 1. Drastrup area location

Diffuse pollution of aquifers is a subject of very high importance in Denmark, since 98% of the drinking water supply comes from underground water, and the transfer time of the water between the surface and the aquifer is generally long compared to most of other aquifers exploited in Europe (Cour des Comptes; 2002). Preserving groundwater

for drinking is not the only subject at stake. In 2001, it was estimated that only 40 % of watercourses and 30 % of lakes met the target set in the regional environmental plans (Wilhjelm Committee; 2001).

To reverse this pollution trend, a project named Drastrup, initiated by the local Government and supported by the LIFE European Commission programme, was begun in 1997.

The main objectives of the project were to ensure that groundwater quality would comply with European drinking water standards and avoid the need to implement the costly treatment measures that would have been necessary if the groundwater protection measures had not been taken.

A costs benefits analysis of groundwater protection measures was undertaken as part of this project. Most of the data used in the report come from that study (European Commission; 2001)[1].

The purpose of the present case study is not to release yet another costs-benefits analysis or fine-tune the Drastrup study, but rather to show to what extent the results of the cost-benefit analysis are determined by the hydro-geological characteristics of the aquifer and by the economic characteristics of the surrounding region. We also show that the results depend to a great extent on the value chosen for the discount rate.

This report is organised as follows. The first section presents the objective and the methodology used. The second section presents the Drastrup project, especially the modification of the land uses it has generated. In the third part, we present the Drastrup project costs-benefits analysis. Then, in the fourth part, a sensitivity analysis is realised.

1. Objectives and method

1.1. OBJECTIVES

The objective of this case study is not to fine-tune the existing costs-benefits analysis of the Drastrup project, but to highlight the diversity of the results that can be obtained using a costs benefits analysis and the impossibility of generalising such results.

Costs and benefits of a water quality restoration programme are both dependant on the actual and future economic activities in the area concerned but also on physical characteristics of the aquifer.

Concretely, the objective of this case study is to demonstrate how:

- two countries, local governments or even municipalities can obtain different results for a same project analysis simply by using different discount rates;
- the costs-benefits analysis can lead to different results for two aquifers having the same physical characteristics but with different potential cost and benefits, especially the loss of agricultural income and the leisure benefits induced by the restoration programme; and inversely for given socio-economic characteristics, but with different physical characteristics of the aquifer;
- The same type of diffuse pollution can lead to different results when both economic and physical characteristics change from one area to another.

[1] European Commission (2001). Sustainable land use in ground water areas. Brussel, European Commission - 28/12/2001. **"LIFE Project" 97/ENV/DK/000347**.

In order to simulate these different physical and economic characteristics, a simplified integrated model as been developed.

1.2. METHODOLOGY USED

The objective of this simplified integrated model is not to illustrate the real interaction of the physical characteristics and the economic activities, or both, but simply to highlight the effects of each of the parameters on the costs-benefits analysis and on the nitrate content in the aquifer.

The Figure 2 illustrates the main interactions between characteristics. The main relations between characteristics are presented in annexe.

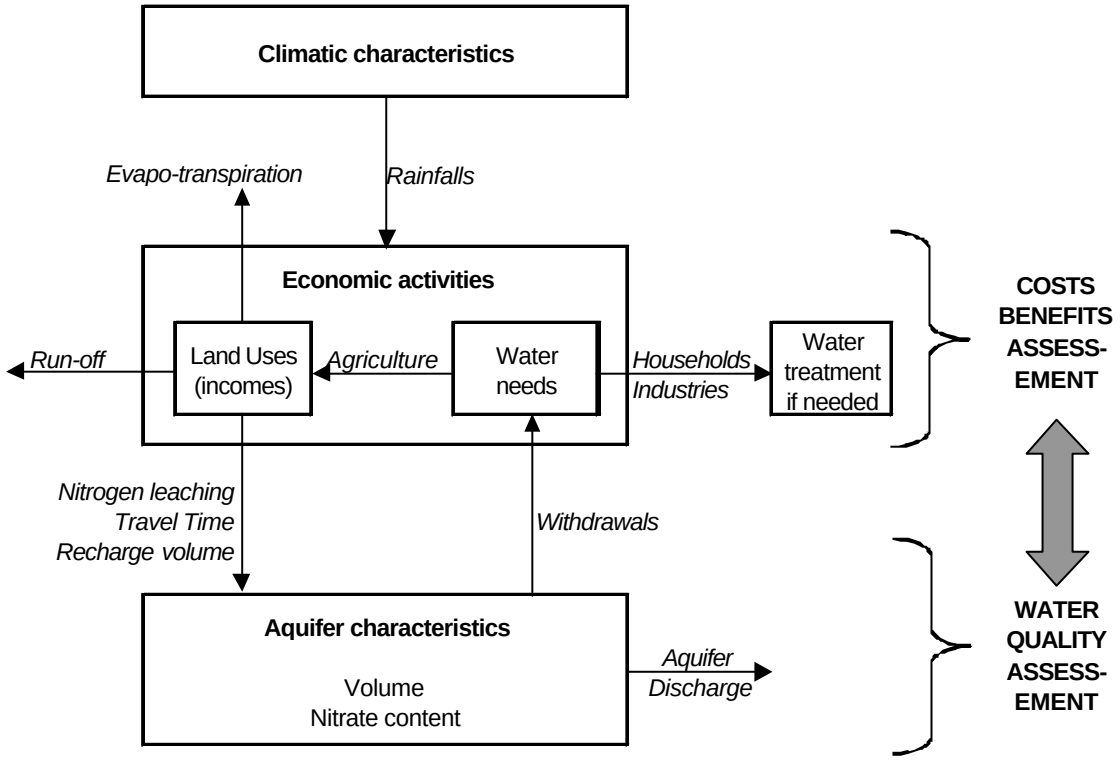

Figure 2. Diagram of the simplified integrated model

♦ **The main physical characteristics are:**

- climate (especially the rainfall and its variability but also all data needed to assess the real evapo-transpiration of cultures (Cappelen; 2002));
- travel time of the water from the surface to the aquifer (in other words, the recharge delay of the aquifer);
- surface run-off (also dependant on the land uses);
- nitrogen leaching (also dependant on the land uses);

- the volume of the aquifer (its porosity, its thickness and its surface)[2];
- the level of useful water reserve of the soil;
- aquifer discharge;

♦ **The main economic characteristics are:**

- the land use which induces different incomes for the economic agents and different nitrogen leaching levels;
- the agricultural, industrial or household sector withdrawals in the aquifer,
- the costs induced for each of these sectors, especially the treatment cost of the water for industrial and households uses;

♦ **The methodology implemented**

The methodology implemented is the following:

- First, using the integrated model, we simulate the evolution of nitrate concentration in the aquifer (over a 50-year period), for various land-use scenarios. The model also estimates costs and benefits for each given nitrate concentration evolution (using the findings of the economic assessment conducted as part of the LIFE project mentioned above). To estimate costs and benefits, 1997 was used as the reference year and all costs and benefits are expressed in € beginning in the year 2000.
- The model was then used to study of the effect that delaying the implementation of restoration measures had on the welfare of society. We tried to answer the following question: Do the prospective benefits of achieving good groundwater status by the year 2015 justify the anticipated cost of the restoration programme?
- Thirdly, the model was used to simulate the sensitivity of the costs and benefits to changes in (i) the hydrogeological characteristics of the aquifer, such as pollutant travel time ; (ii) the economic characteristics of the surrounding region ; (iii) the discount rate value chosen to assess future costs (in current monetary units) and benefits, and (iv) a combination of all of these elements.

For each simulation, we use the Monte Carlo method to generate 50 climatic conditions (average rainfall = 712 mm and standard deviation = 50 mm) (Cappelen; 2002), in order to assess the average nitrate concentration in the aquifer and the potential costs and benefits averages.

[2] In the model, no distinction is made between aquifer layers. The aquifer recharge volume is supposed to mix with the entire aquifer volume as soon as it reaches the water table.

2. The Drastrup project

A costs-benefits analysis consists of comparing the forecasted costs and benefits of a groundwater remediation scenario with the anticipated costs and benefits of a business-as-usual scenario. In the present case, the business-as-usual scenario represents the continuation of the intensive agriculture that prevailed before 1997, whereas the remediation scenario is the afforestation and pasture programme: the Drastrup project.

2.1. THE BUSINESS AS USUAL SCENARIO AND THE POLLUTION INDUCED

The physical characteristics as well as the economic activities prevailing before the project need both to be identified and forecasted. This implies assessing the impact of the continuation of the intensive agricultural land use on the water quality and on the costs and benefits induced for each sector identified.

The 1997 land use was characterised by 900 hectares of intensive agriculture and 100 hectares of residential area near the village of Frejlev. The quality of the water aquifer was affected by nitrate and pesticide diffuse pollution originating from the agriculture activity (organic and chemical fertilisers and pesticides) and from resident gardening activities (chemical fertiliser and pesticide).

The Figure 3 illustrates the nitrate level in the groundwater. The youngest groundwater contains the highest level of nitrate. This is partly due to the denitrification process through the ground and the aquifer, but especially to various amounts of nitrogen leaching in past years, as well as to the dilution of nitrate in the lower layers that are less polluted by past activities. The water withdrawn at 15 m from the ground was about 25 years old in 2000 and was the most polluted. Over the past 25 years, nitrogen leaching has decreased significantly. The Wilhjelm Committee (2001) estimated that during the period 1990 – 1999, the average reduction in leaching of nitrogen from Danish arable land was about 32 %.

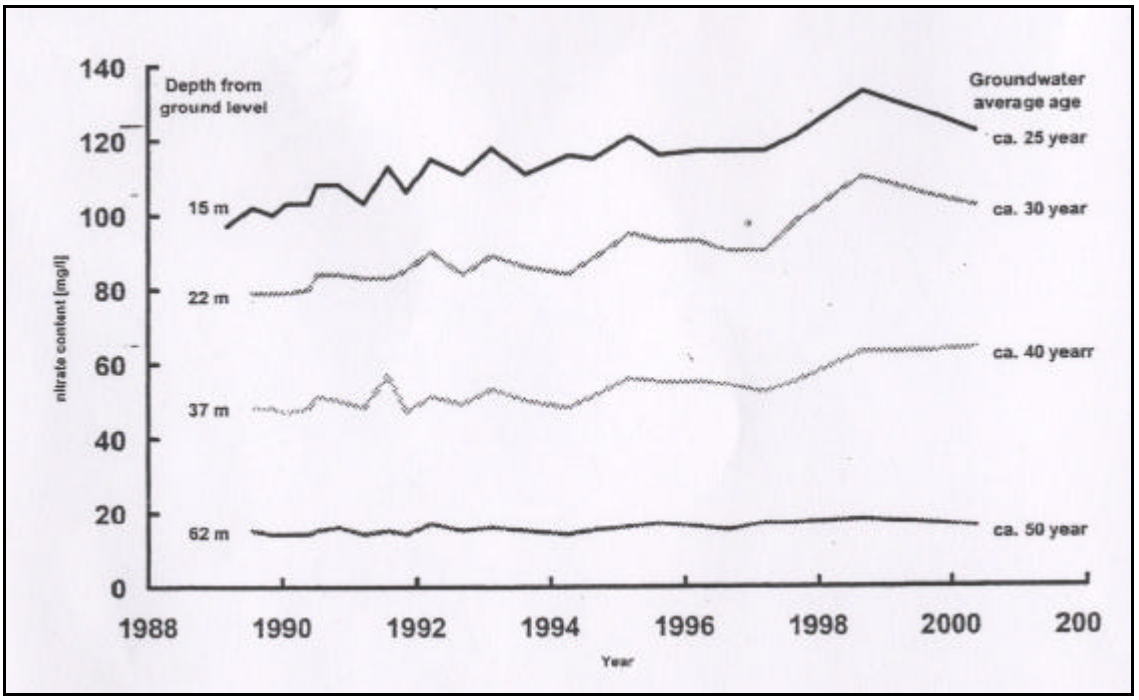

Figure 3. Nitrate level in the groundwater. Source (European Commission; 2001)

Considering the national trend in nitrogen leaching, data from the Danmarks Statistik (2003), and the figure above, we've assessed the nitrate content of annual infiltration, that is to say the content of the water travelling in the successive layers. Figure 4 illustrates this evolution and assumes zero denitrification. Considering a 20-year travel time for the water, the 20 next years should be still characterised by an increasing nitrate content in the aquifer, since the nitrate content of the recharge will be still more than 120 mg/l. No quality improvement will probably be noted before year 2020, in other words in 20 years if we assume an implementation of the measure in 2000 (the reference year).

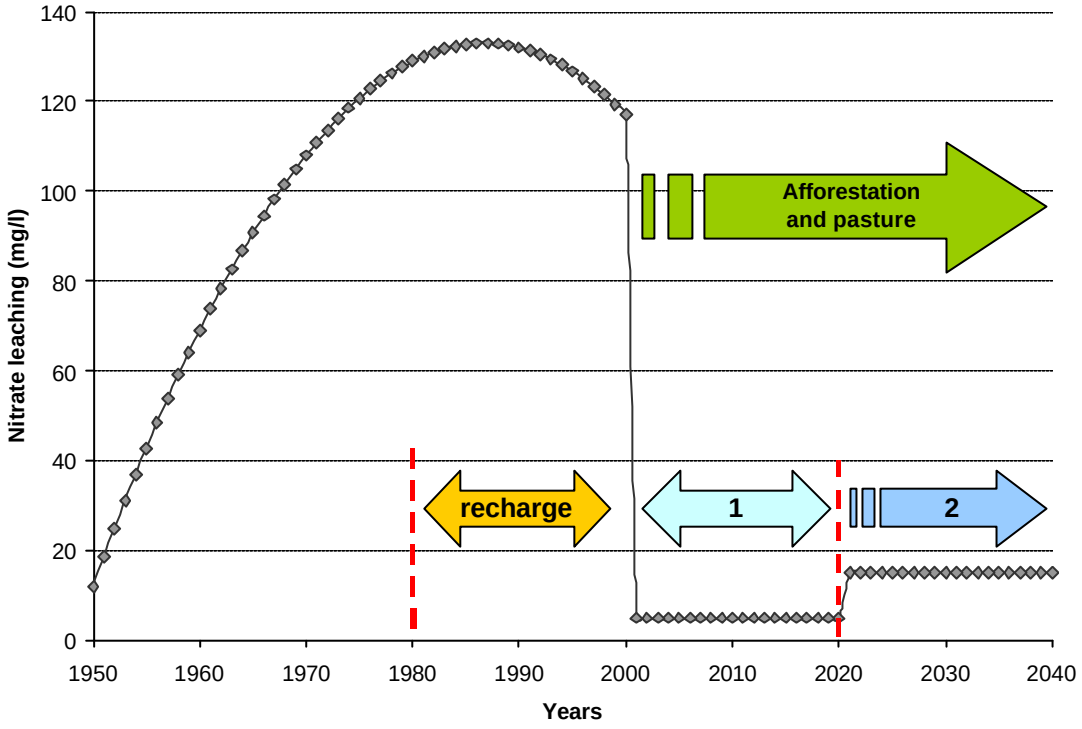

Figure 4. Evolution of nitrate leaching

2.2. THE DRASTRUP AFFORESTATION AND PASTURE SCENARIO AND THE POLLUTION INDUCE

To restore the quality of the groundwater it has been decided to turn the 900 hectares of intensive agriculture area into 500 hectares of forest and 400 hectares of pasture. This restoration programme is highly innovative. The Aalborg municipality bought some land, planted trees on it and then sold it. Mouritsen, Staunstrup et al. (2002) have shown that this property restructuring method is structurally and financially more sustainable than the subsidy payment method. The Drastrup afforestation was thus financially neutral since the tree plantation was largely supported by the European subsidies and Life Project.

However, in some instances, negotiations between farmers and the municipality did not succeed. Therefore, the municipality had to buy declaration on the land and thus prohibit the use of manuring, spraying, etc. Consequently, farm production would stop and the water quality could, to some extent, be improved.

Concerning the permanent grass cover, Aalborg municipality has made an agreement

with farmers. In this agreement, the grazing pressure has been determined from a precautionary principle, which was 0,5 animal unit per hectare during the growing season. The objective here is to ensure a varied herbal-like flora with a close vegetation cover that can absorb the animals' manure.

A parallel programme had consisted of informing the citizens on the consequences of the pesticides and other chemicals used. The results of that action, called "Pesticide Free Town", was a real success, since in 2001, only 12 % of the citizens did remain users of such substances.

These friendlier practices will lead to a net reduction of diffuse pollution, especially of nitrogen leaching. Figure 4 illustrates the potential nitrate leaching in the annual infiltration after project implementation (after 2000 in the figure). The period numbered 1 is characterised by very poor leaching, essentially due to the content of the rainfall. Period 2 is characterised by higher nitrate content, since nitrate leaching will increase when the forest is more than 20 years old. The real assessment of the nitrate leaching is still uncertain, but scientists estimate that leaching from the oldest forest will remain significantly lower than with conventional agriculture. This is why, in Figure 4, we consider the average leaching in the recharge area equal to 15 mg/l.

3. The Drastrup costs-benefits analysis

3.1. NATURE AND ASSESSEMENT OF COSTS AND BENEFITS

The first step of the costs benefits analysis consists of identifying the types of costs and benefits accruing to various agents and economic sectors for the two scenarios. The four main sectors affected by the Drastrup project are: (i) agriculture, (ii) water supply, (iii) the environment and (iv) households benefiting from the amenities and recreational possibilities offered by the new forest and commons.

♦ The agricultural cost

The main cost of the groundwater remediation programme is the loss of income for the agricultural sector, the land being shifted from intensive production to permanent grazing and forest. The loss is estimated at 290 € per hectare, or 261.000 € per year (Table 1).

♦ The benefits

The first objective of the project was of course to improve the groundwater quality to respect drinking water norms, but also to avoid or limit high future treatment costs of the water. The project would also have a positive impact on the environment and on leisure activities.

Reduction of treatment costs for the drinking water sector depends on the evolution of the nitrate concentration in the aquifer, and the drinking water suppliers will have to invest in water treatment as soon as the nitrate content exceeds 50 mg/l. In that case, the treatment cost per cubic meter is estimated at 0.2 € (Lacroix and Baldichi; 1995; Cour des Comptes; 2002), or a total annual cost of 440,000 € (this amount seems to be a minimal value) (Table 1).

Environmental benefits essentially concern the reduction of CO_2 emissions due to the development of the forest: The value of the related environmental benefits is assessed using the value of the Danish CO_2 tax per ton of CO_2 multiplied by the total quantity of CO_2 absorbed by the new forest. Assuming an absorption capacity of 8 tons per year and per hectare and a price of 13.5 €/ton CO_2, it leads to an environmental benefit of 54,000 €/year during the first 90 first years of the forest (Table 1). The projects have also other positive effects on the environment, such as the growth in the wildlife as well as in the flora and fauna diversity. Because of the difficulty of assessing these last benefits, they will not be integrated into the calculation as well as the effect on lake eutrophication and water course reduction in pollution.

Amenities or leisure benefits are also indirect benefits of the project because they create new recreational opportunities for the inhabitants of a densely populated and urbanised area. Since the new forest is located near a residential area, the economic value of the amenities created by the project has increased property values. This increase was used to estimate the economic value of the amenity (hedonic price method), which is estimated at 375,000 € per year (Præstholm, Jensen et al.; 2002) (Table 1). This value is not only due to the presence of the forest but also to the development of the recreational area and to the advantage it offers to visitors. Olds gravel pits have been developed and turned in picnic areas, 55 km of paths allow the visitor to see trails and buildings from the Iron Age.

	Business as usual scenario	**Drastrup scenario**	**Drastrup net benefits**
Agriculture	261.000 €	0 €	- 261.000 €
Drinking water supply	- 440.000 € in years in which water is treated		
Leisure activities	0 €	375.000 €	375.000 €
Environment	0 €	54.000 €	54.000 €
Net social benefits excluding drinking water supply			**168.000 €**

Table 1. Annual net benefit of the Drastrup Project *(negative benefits are costs)*.

3.2. DRASTRRUP PROJECT RESULTS

The project results are both analysed in terms of future water quality improvement and net social benefits.

- **The water quality**

The model was first used to simulate the impact of the Drastrup project on nitrate concentration in the aquifer. The results show that, due to the length of time it takes for water to percolate through the unsaturated zone, the nitrate concentration might increase for 20 years and exceed 50 mg/l before starting to decrease. During the first 20 years, the nitrate concentration will continue to rise even if the surface nitrogen leaching is eliminated.

Aquifer nitrate content should then be lower than the norm during the 10 – 15 years following the project, exceed 50 mg/l for the next 10 – 15 years (period when treatment is needed) and then be below the norm nearly 25 years after project implementation

(see Figure 5). This confirms the LIFE project conclusion (European Commission; 2001).

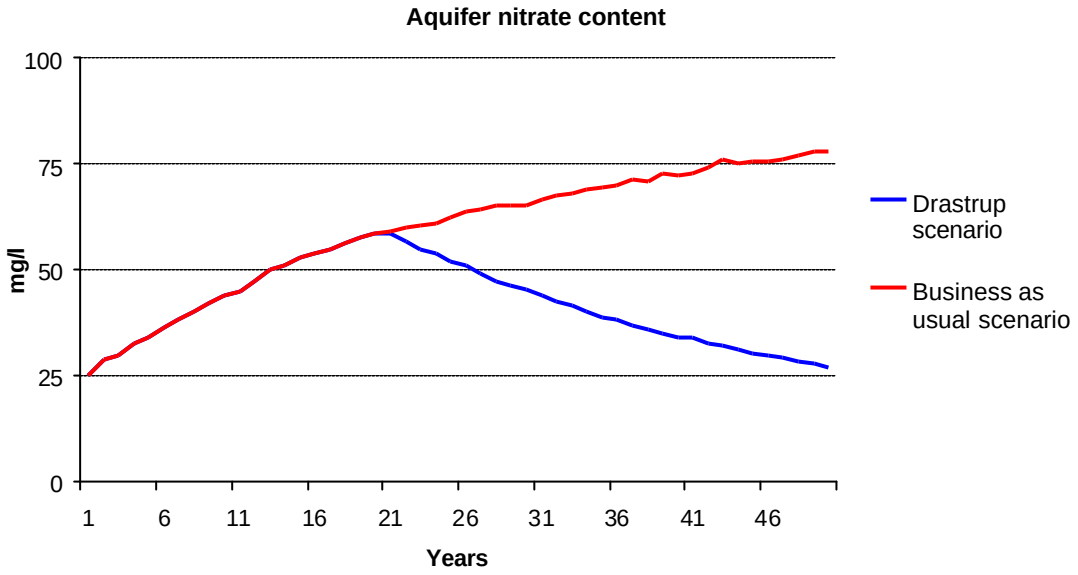

Figure 5. Simulation of the evolution of the nitrate concentration in abstracted groundwater.

♦ **The net social benefit over the whole life of the project**

The integrated model also shows that the Drastrup project creates a high positive net social benefit as soon as it is implemented: about 10 million € using a 3 % discount rate (first bar in Figure 7). Afforestation is preferable to conventional agriculture from a social point of view because of the high amenity benefits it produces.

Therefore, the afforestation of the Drastrup catchment area to restore groundwater quality is a programme that does not need any incentives or statutory constraints to be adopted. The net benefit enables the local government to compensate different interest groups without imposing a financial loss on any of them.

4. Sensitivity analysis

In order to illustrate the variability of the results that can be obtained in rather similar case studies, we reproduce the Drastrup costs benefits analysis modifying first one of the model parameters, and then several of them simultaneously.

4.1. IMPACT OF DELAYED IMPLEMENTATION ON COSTS AND BENEFITS

We then simulated the impact of a delayed implementation of the remedial measures. The results show that such a delay would require maintaining drinking water treatment over a longer period and would also delay the date at which drinking water standards are met (Figure 6).

As a result, any delay would reduce net social benefits. Figure 7 illustrates this relationship where a 5-year delay would reduce the benefits by 27 % and a 10-year delay would cut them in half.

Delaying the implementation of the Drastrup project will then lead to lower net social benefits and worsen future groundwater quality. From that point of view, the Danish property restructuring method is particularly effective, since it accelerates the afforestation and pasture programmes.

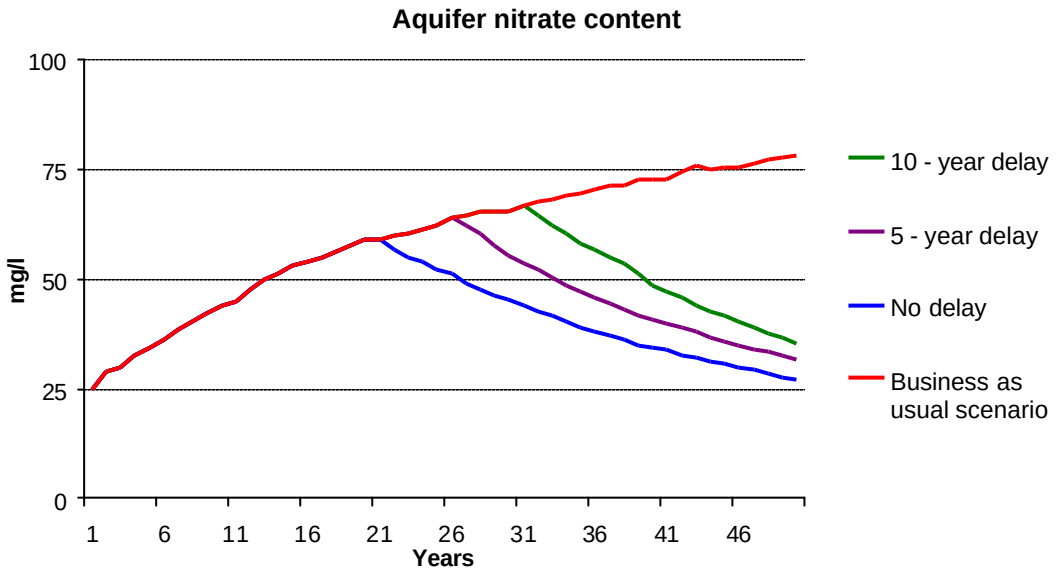

Figure 6. Simulation of the evolution of the nitrate concentration in abstracted groundwater for various implementation delays.

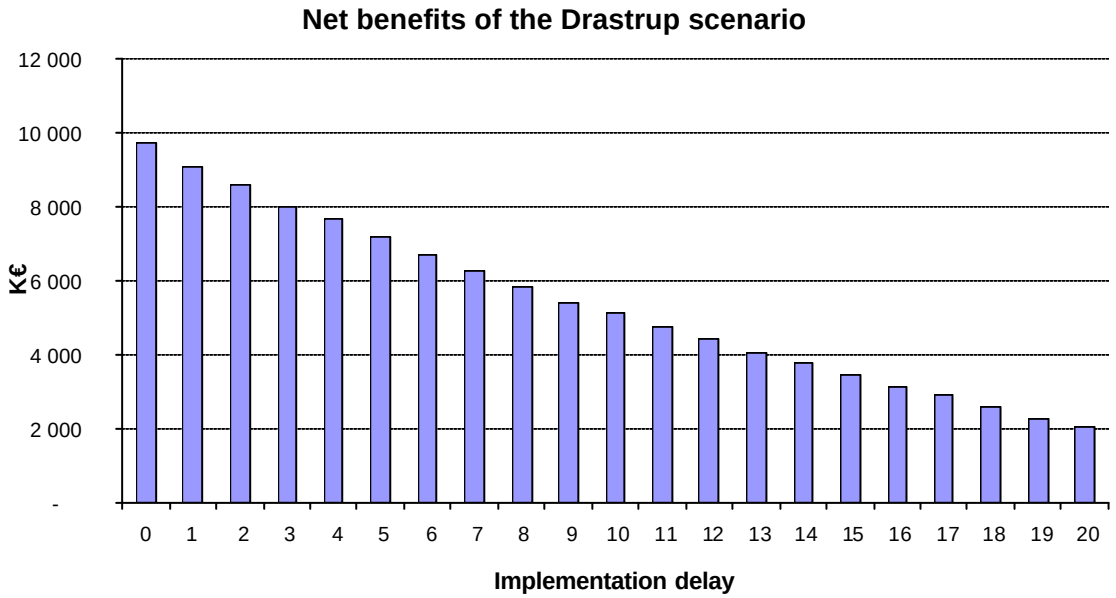

Figure 7. Evolution of the net social benefit of the afforestation programme as a function of the implementation delay.

4.2. SENSITIVITY TO ECONOMIC ACTIVITIES AND PARAMETERS

The results of the costs-benefits analysis are highly dependent on two economic parameters: the discount rate and the significance of recreational benefits created by the forest.

♦ Sensitivity analysis of the discount rate

The results of the costs-benefits analysis depend partly on the discount rate used (a high discount rate reduces the current value of future costs and benefits). The analysis of a given case study can therefore produce different results depending on the discount rate recommended by the national authorities. In Denmark, the United States and Norway, the recommended discount rates vary from 2 or 3 % to 7 or 8 % (Dubgaard, Kallesoe et al.; 2002). In Great Britain, a single 6 % rate is recommended.

To illustrate this, we repeated the above costs-benefits analysis[3] but with a 6 % discount rate. Assuming all other factors remain unchanged (i.e., no implementation delay), changing the discount rate from 3 to 6% results in a 65 % reduction of the net social benefit (Figure 8). Using a 10 % discount rate rather than 3 %, as do private companies or even the World Bank, the net social benefits is near to nil since the variation it induces compared to a 3 % is about 85 % (the net benefits is then 1,6 rather than 9,8 million €).

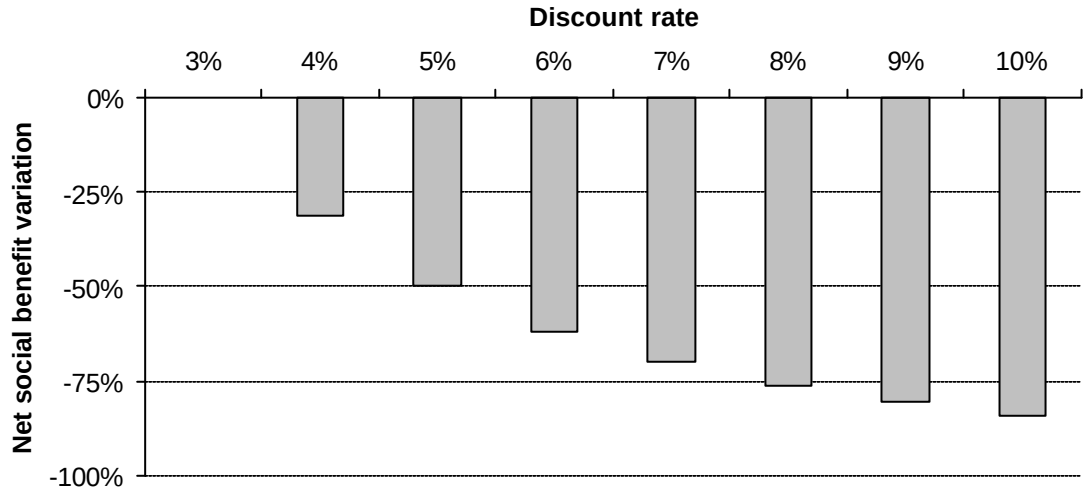

Figure 8. Net social benefit variation for different discount rate values compared with a 3% discount rate

♦ Sensitivity to the recreational benefits

The high recreational benefits of the Drastrup afforestation programme are largely due to the presence of a residential area near the new forest. As shown by Danish studies (Præstholm, Jensen et al.; 2002; Erichsen, Hasler et al.; 2003), the recreational value of the forest would be significantly lower if the residential area were not in such close proximity. Using the hedonic price method (HPM), the authors have shown that the value of the recreational benefit generated by the forest would decrease by 5 to 10 %

[3] The above analysis is made using a 3 % discount rate.

for each extra kilometre between the houses and the forest.

Moreover, environmental goods being similar to economic ones, they only have a high value when they are rather rare. With a wooded countryside, the extra value induced by a new forest would be near nil, even negative in certain cases.

In both cases, wooded countryside and sparsely populated area, the project would become socially costly. If we consider a zero recreational benefits, the net social benefit would become negative, estimated at -2.8 million € for an immediate implementation. This high net social cost does not justify any delay of implementation, since any extra delay increases it.

4.3. SENSITIVITY ANALYSIS OF THE POLLUTANT TRAVEL TIME BETWEEN THE SURFACE AND THE AQUIFER

Results are also very dependent on the travel time of pollutants between the surface and the aquifer. In the Drastrup area, this duration was estimated to be 20 years. This assumption does not take into consideration the fact that nitrate transfer in the unsaturated zone is a very complex phenomenon. At a given place, nitrates might migrate at various speeds (existence of preferential migration paths). Therefore, this assumption (as well as the results of the simulations) should be seen simply as a necessary step in the economic analysis and not as a deterministic representation of the natural processes.

If the travel time is 10 years instead of 20[4], the net social benefit of the project would increase by 44 %. This is mainly due to the fact that the period during which drinking water has to be treated would be shortened.

These results illustrate that knowledge of the economic activities and potential benefits of a restoration programme do not allow for any generalisation of results.

4.4. SENSITIVITY TO COMBINED VARIATION

The model was also used to study the *combined effect* of changes in all of the above parameters: (i) delay in implementation of the programme (from 0 to 20 years); (ii) presence of recreational benefits (with or without) and (iii) pollutant travel time (10 or 20 years).

- **The combined impact of changes in pollutant transfer and implementation delay**

A first simulation was done to assess the combined impact of changes in pollutant travel times and delayed implementation. Table 2 shows that the shorter the pollutant travel time, the less subject the net benefits of the afforestation programme are to a delayed implementation. For some pairs – travel time / implementation delay – the loss of net benefit induced can be considered as low (grey cases in the table 2).

In such cases, decision-makers might wish to delay the implementation of an afforestation programme if they anticipate a possible increase in agricultural revenues, a loss in the attractiveness of the forest, or when suppliers anticipate a reduction in

[4] Such variations in the travel time of the water are frequent and can even be found in different places in the same aquifer.

treatment costs through technological progress.

In certain cases, especially in the case mentioned above where the net benefits variations are small, the integration of the risk and uncertainty either in economical or physical parameters of the model could easily explain why decision-makers prefer waiting. When such decision-makers are politicians, a model of political-economic interaction could certainly also explain such decisions.

Whether or not to delay the afforestation programme depends on the status of the decision-maker, and especially on his own perception of its popularity, but also on physical characteristics if these are known.

When the decision is likely to be uncertain, it could be preferable either to transfer the decision to another official or to impose statutory constraints.

	Implementation delay		
Pollutant travelling time	**5 years**	**10 years**	**15 years**
5 years	-5 %	-10 %	-13 %
10 years	-5 %	-16 %	-41 %
15 years	-27 %	-46 %	-62 %
20 years	- 27 %	-48 %	-66 %

Table 2. Net benefit variation of the remedial programme induced by a 5, 10 and 15-year delay and for various pollutant travel times.

- **The impact of changes in three parameters**

A second simulation was done to assess the impact of changes in three parameters. Figure 9 below illustrates the evolution of the net social benefit of the Drastrup project for a pollutant travel time of 10 years, with and without recreational benefits. The absence of recreational benefits divides the potential net social benefit by 10.

In the absence of recreational benefits, therefore, it is socially desirable to delay the implementation of the remedial programme, because the net social benefit increases with time, with an optimum date after 8 years. The 8-year delay allows doubling of the potential benefits, whereas delaying the implementation when high potential recreational benefits exist, lead inevitably to a reduction of the social benefits.

When benefits increase or cost decreases with the implementation delay, the economic rationality would suggest that the implementation of the programme be delayed as long as it will not be necessary to treat future water withdrawals.

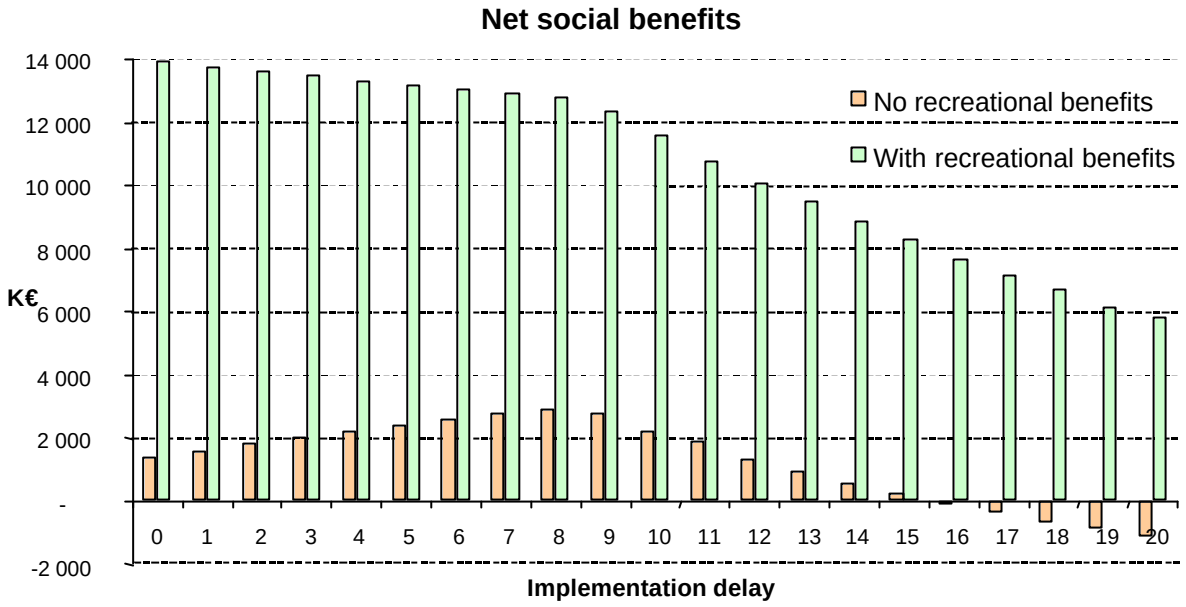

Figure 9. Impact of implementation delay on the net social benefit of the forestation programme for 2 recreational benefit scenarios (with recreational benefits and without) and assuming a 10-year pollutant travel time.

Conclusions and implications

This case study shows that, in some aquifers, nitrate concentration can continue to an increase in spite of intensive measures taken to reduce or even eliminate pollution sources. Therefore, due to natural constraints such as pollutant travel time, the trend reversal clause of the Groundwater Directive might be difficult to apply. The aquifer pollution content will not be a good indicator of the effort made to restore the quality of the aquifers and a full monitoring of aquifers seems to be too costly. In such cases where the inertia of aquifers is high, a surface monitoring of the economic activities would certainly be more effective.

Secondly, the case study shows that costs and benefits of groundwater protection measures are highly dependent on local economic and physical conditions. Therefore, would seem very difficult to draw general conclusions on the net economic benefits that can be generated by different levels of groundwater protection for the purpose of generalising such results and preventing high aquifer monitoring costs.

Thirdly, this case study proves that the use of a different discount rate can lead to completely different results. If economic valuation is to be used by Member States as a decision support tool, especially for arguing dispensations for failure to comply with the Water Framework Directive, a common discount rate must be used so that cost-effectiveness analyses as well as costs-benefits analyses can be compared on the same basis.

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Annexe

Socio-economic parameters

a = discount rate

$S_{i,t}$ = surface of culture "i" on the surface aquifer refill zone (ha)

A_i = agricultural annual net benefit for 1 ha of culture "i"

E_i = total annual benefits for the environment due directly or not to the culture "i"

R_i = total annual benefits for the recreational uses due directly or not to the culture "i"

WS_t = aquifer withdrawals of potable water suppliers (m^3)

WI_t = aquifer withdrawals of industries (m^3)

Ibp = industry break point that is to say the level of nitrate content of the aquifer upper which it is necessary to treat water

Sbp = supplier break point

ITC_t = annual industry treatment cost

STC_t = annual supplier treatment cost

Agronomic and climatic parameters

t = suffix designing the year considered

i = suffix designing the type of culture

$S_{i,t}$ = surface of culture "i" on the surface aquifer refill zone (ha)

r_i = superficial run-off rate

$RO_{i,t} = r_i \,.\, RF_t$: run-off (m^3)

RF_t = annual rainfall (mm)

$ETP_{i,t}$ = potential evapotranspiration (mm)

k_i = cultural coefficient

$ETR_{i,t}$ = real evapotranspiration (mm)

- if $k_i \,.\, ETP_{i,t} < RF_t(1-r_i) - RO_{i,t}$ then $ETR_{i,t} = k_i \,.\, ETP_{i,t}$
- if $k_i \,.\, ETP_{i,t} \geq RF_t(1-r_i) - RO_{i,t}$ then $ETR_{i,t} = RF_t(1-r_i)$

N_i = nitrogen brought (kg/ha)

l_i = nitrogen losses rate

$(NO_3)_i = \mathrm{mwr}.N_i.l_i$: nitrate lost (kg/ha) where "mwr" is the ratio of the molecular weight of nitrogen compare to nitrate

Aquifer characteristics

r = suffix designing the time lag between rainfalls and aquifer refill (depends of the height of the unsaturated zone and of its porosity)

AMV = maximal aquifer volume (m^3) upper which each additional cubic meter is considered as aquifer outflow (usually depends on thickness, porosity and surface of the aquifer)

AV_0 = present aquifer volume (m^3)

AR_t = aquifer refill (m^3):

- if $RF_{t-r} > ETP_{i,t-r}$ then $AR_t = \sum_i \left(S_{i,t-r} \left[RF_{t-r} (1 - r_i) - ETR_{i,t-r} \right] . 10^{-3} \right)$
- if $RF_{t-r} \leq ETP_{i,t-r}$ then AR_t should be nil but we'll consider it equal to 1 m^3 to allow dilution of the nitrate lost in year (t-r)

AO_t = aquifer outflow (m^3)

- if $AV_{t-1} + AR_t - WS_t - WI_t < AMV$ then $AO_t = 0$
- if $AV_{t-1} + AR_t - WS_t - WI_t \geq AMV$ then $AO_t = AV_{t-1} + AR_t - WS_t - WI_t - AVM$

AV_t = aquifer volume (m^3)

- if $AO_t \geq 0$ then $AV_t = AMV$
- if $AO_t < 0$ then $AV_t = AV_{t-1} + AR_t - WS_t - WI_t$

ARN_t = nitrate content of the aquifer refill (mg/l) : $ARN_t = \sum_i \frac{(NO_3)_{i,t-r} . S_{i,t-r} . 10^{-3}}{AR_t}$

AN_t = nitrate content of the whole aquifer (mg/l) : $AN_t = \frac{ARN_t . AR_t + AN_{t-1} . V_{t-1}}{AR_t . V_{t-1}}$

BRGM

WATER DEPARTMENT

Resource Assessment and Discontinuous Aquifer Unit

BP 6009 – 45090 Orléans cedex 2 – France – Tél. : 33 (0)2 38 64 34 34