Integrated Assessment
2002, Vol. 3, No. 4, pp. 321–342

1389-5176/02/0304-321$16.00

Cost-Effective Nutrient Emission Reductions in the Rhine River Basin

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ABSTRACT

Nitrogen and phosphorous emissions in the Rhine river basin and measures and quota restrictions to reduce them are distinguished between in an optimisation model which calculates how to reach a desired load to the North Sea in a cost-effective way. Nutrients are emitted by farm types (at most 10 per region) and wastewater and sewage treatment plants in 13 regions and nutrients are retained by wetlands at the basin level. Cost abatement curves are fitted for each agricultural sector using the output of a simulation model which describes the interaction between agriculture, industry and wetlands. The cost effective solution suggests to substantially abate emissions by constructing wetlands. A sensitivity analysis with the model shows that if the climate becomes wetter, possibly due to climate change, the emissions of agricultural sources gain importance and more measures should be taken at the farm level, reducing the total cost by 1.6% as compared to the case without climate change.

Keywords: cost-effectiveness, nutrients, optimisation, Rhine river basin, water quality.

1. INTRODUCTION

The primary objective of this paper is to find a cost-effective allocation of nutrient abatement by agriculture, wastewater and sewage treatment plants (WWTPs) (covering both households and industry) and wetlands in the Rhine river basin in order to reduce nutrient loads to the North Sea at least costs. As many environmental economists have shown, a uniform emission reduction rate will most likely not be the cost effective solution to such a problem (Schleich et al. [1]; Ruff [2]; Tietenberg [3]). This paper performs a cost-effectiveness analysis using a model, which can deal with nitrogen (N) and phosphorous (P) simultaneously.

As long as nutrient abatement options are limited to measures that have only effect on either N or P, a model consisting of a set of independent equations can be used (see, for example, Van der Veeren and Tol [4]). However, quota restrictions as well as certain measures reduce N and P simultaneously (not always in the same proportions). These interactive effects can not be included properly in such a model. As a possible way to work around this problem, Van der Veeren [5] presents a two step procedure. Since most nutrient emitting sources have no technical opportunities to reduce P emissions, the first step was to perform a cost-effectiveness analysis for P only. The cost functions for N abatement are then estimated, given the P abatement restrictions imposed by the cost-effective allocation from the first step. The second step then consists of a cost-effectiveness analysis for N emissions using these new cost functions. Although this procedure does provide a way to include measures with different impacts on N and P emissions in one model, the results may not be cost-effective, but they are locally optimal.

Therefore, this paper presents an alternative model, which calculates the cost-effective joint N and P emission reduction in the Rhine river basin, to achieve a desired load to the North Sea. The optimisation model simultaneously considers diffuse emissions from farm types (at most 10 per region) and point emissions from WWTPs in 13 regions and nutrient retention by wetlands. Besides a differentiation between N and P in the model, a further differentiation is made between measures and quota restrictions to reduce nutrient emissions. In combining N and P, we are facing a problem in defining an appropriate cost function because some measures can be targeted on either one specific nutrient alone, or on both nutrients in combination. Furthermore, some combined measures have different physical constraints such as the most stringent quota restriction, namely farm closure (this measure by definition reduces all N and P emissions simultaneously) or a joint reduction through measures at farms (the proportional reductions percentages can vary for N and P).

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This study considers nutrient abatement options by agricultural sources and WWTPs covering approximately 95% of nutrient emissions (RIVM [6]).

Since plants and animals living in regional surface waters take up some of the nutrients (this process is also referred to as retention), differences in the length of regional surface waters before reaching the mainstream of the Rhine result in differences in retention. This means that the fraction of nutrient emissions entering the Rhine is generally lower for regions located further away from the mainstream. According to Lorenz [7] biochemical and ecological processes hardly take place in the mainstream of the Rhine, due to water flow. Following this result, we assumed that all nutrients entering the main river will finally reach the river outlet.

In addition, the effects of nutrient abatement measures on surface waters differ significantly between agricultural sources and point sources (such as WWTPs). Changes in the animal's diet, stable adjustments and improved manure management are considered as measures at the farm level (see Table AI.2). Since part of the excess amounts of nutrients applied on agricultural land is retained in biochemical processes in the soil, not all of the nutrients emitted by agricultural sources ultimately end up in surface water. Point sources, however, are most often direct emitters. Almost all nutrients emitted by these sources end up in regional surface waters. Whereas this study does discriminate between the impacts of point sources and agricultural sources, we assumed that the impact of nutrient emissions on the loads to the North Sea are the same for the various agricultural sources within one region.

Transport coefficients are used as a linear fix for the impact of emission sources on the sink (in this study the North Sea). These transport coefficients are a simple representation of transport mechanisms taking place in the river basin. They describe how much of the emissions reach the river and eventually the North Sea. In cost-effectiveness analyses, such as the one presented here, simple representations are preferred, since using more sophisticated water quality models may increase both model size and calculation time considerably (see also [4] for a more extensive discussion on transport coefficients and their values). Since hydrological variations may have important consequences on run-off, discharge, and retention, Section 4 applies sensitivity analyses on the impact of changes in values of the transport coefficients.

The question at hand is: "How to find a cost-effective solution for a given target on nutrient loads?" This paper will present a method to do so, together with the results for a situation in which the loads for N and P to the North Sea in the baseline in 2015 have to be reduced by 30%. In the baseline no measures are taken, while the economy develops as described by the European renaissance scenario, which is taken from the CPB (Otto et al. [8]). Under this scenario, a load reduction will be achieved of 25.3% N and 56.3% P by 2015 with respect to the load in 1985. Hence, in the base case of this paper, where an additional reduction of 30% N and P is considered, a load reduction is achieved of 47.7% N and 69.4% P with respect to the load in 1985. The model itself is more general and can also be applied to calculate the cost-effective allocation for other targets.

Section 2 presents the optimisation model used for the cost-effectiveness analysis. The model description starts at source level, it is then aggregated to represent one region and, finally, the model is aggregated to the Rhine basin.

Section 3 describes how the parameters of the optimisation model (see Appendix I) are estimated, which is an interaction between software packages. Data are obtained from the computational framework (CF) of the Sustainability and environmental Quality in transboundary River basins (SQR) project (Tanczos [9]).

Section 4 presents the results of the model described in Section 3. We start with a discussion on the cost-effective allocation of nutrient emission reductions, for a situation in which the target is a 30% reduction in nutrient loads to the North Sea for N and P simultaneously. We describe the consequences for the various regions and the various sectors. We limit ourselves to the main characteristics of the optimal allocation, and leave the details for Appendix II.

The allocation of nutrient abatement options will only be optimal for the given set of parameters. Some of the values of these parameters are not certain (for example, the effectiveness and costs of nutrient retention by wetlands [9]), whereas others may change in time (for example transport coefficients, and technological constraints). Therefore, the consequences of such changes in parameter values on the cost-effective allocation are also analysed. Finally, a cost optimal solution for the well-known policy targets from the OSPAR agreement of 50% N and P load reduction in the short run and 70% N and 75% P load reduction in the long run are also given.

We draw conclusions in Section 5 together with recommendations for future research activities. The estimated parameters of the optimisation model and detailed results of the sensitivity analyses are provided in the appendices.

2. THE OPTIMISATION MODEL

We first present a general model for three intrinsically different sectors, namely farms, WWTPs and wetlands. These three sectors have very different methodological consequences as we explain below. An extension of the problem to multiple regions and multiple sectors can be achieved by expanding a matrix.

Table 1 shows the eight different variables of the model, which represent an additional reduction of nutrients at the

Table 1. Variables in the optimisation model.

Nitrogen	Phosphorus	Description
N_M	P_M	emission reduction by measures at farms [kton]
N_Q	P_Q	emission reduction by quota restrictions on farms [kton]
N	P	emission reduction by measures at waste water treatment plants [kton]
n	p	load reduction in North Sea due to nutrient wetland retention [fraction]

Table 2. Parameters in the optimisation model.

Nitrogen	Phosphorus	Description
T_N	T_P	Transport coefficient at farms [fraction]
T_{Ni}	T_{Pi}	Transport coefficient at waste water treatment plants [fraction]
h_m	h_q	Quadratic term in cost function for measures at farms [M€/kton^2]
h_n	h_p	Quadratic term in cost function for waste water treatment plants [M€/kton^2]
h_w		Quadratic cost for reducing a fraction of the load through wetlands [M€]
c		Avoidable costs in initial situation [M€]
g_m		The amount of N required to reduce a unit of P for measures at farms [fraction]
g_q		The amount of N required to reduce a unit of P by quota restrictions on farms [fraction]
g_w		The amount of N required to reduce a unit of P for wetlands [fraction]
Ntar	Ptar	Reduction target for nutrient load to the North Sea [fraction]
Nmax	Pmax	Maximum fraction of reducible emissions by measures at farms [fraction]
Nmaxi	Pmaxi	Maximum fraction of reducible emissions by waste water treatment plants [fraction]
Nmaxw	Pmaxw	Maximum fraction of reducible load to the North Sea by wetlands [fraction]
N0	P0	Initial emissions by farms [kton]
N0i	P0i	Initial emissions by waste water treatment plants [kton]
AeqN	AeqP	Initial load to the North Sea [kton]

source level in 2015, as compared to the baseline situation in 2015. These variables are conditioned by the parameters in Table 2.

The model trades off among a joint N and P reduction, measures and quota restrictions at the farm level, measures at WWTPs and wetland construction. Measures at the farm level and the construction of wetlands are assumed to lead to a joint reduction of N and P in fixed proportions. In the model, it is assumed that these emission reductions are linked linearly, using Equation (1).

$$\begin{aligned} N_M &= g_m P_M; \quad \text{where} \quad & g_m &= \frac{\text{Nmax}}{\text{Pmax}}\frac{\text{N0}}{\text{P0}} \\ N_Q &= g_q P_Q & g_q &= \frac{\text{N0}}{\text{P0}} \\ n &= g_w p & g_w &= \frac{\text{Nmaxw}}{\text{Pmaxw}} \end{aligned} \tag{1}$$

These linear links reduce the number of variables in the model from 8 to 5, as three variables in the model can always be substituted by other variables by applying Equation (1).

From now on, we continue to work with N_M, P_Q, N, P and n. For each variable we assume that the costs increase quadratically. A constant term (c) is added to the cost function to account for the cost difference between a possible suboptimal initial situation and an optimal initial situation as represented by Equation (2).

$$\text{Cost}(N_M, P_Q, N, P, n) = h_m N_M^2 + h_q P_Q^2 + h_n N^2 + h_p P^2 + \\ + h_w n^2 - c \tag{2}$$

Hence, the model allows for an amount of c Euros to be earned. This is done because, in an actual situation, it does not need to be the case that all agricultural (and industrial) sectors reduce nutrients optimally. In other words, the inclusion of 'c' allows us to model a situation where agricultural (and industrial) sectors can reduce nutrients and save costs at the same time. Specification (2) reflects that, in the optimal initial situation, all measures with maximal nutrient reduction at negative cost are taken (see also Section 3).

The assumption of a quadratic cost function implies that a measure will cost relatively more if the level of implementation increases. The quadratic form further avoids an undesired solution where measures are either implemented for 100% or 0%, a so-called bang-bang solution.

The model is further restricted by inequality constraints in order to integrate measures and quota restrictions, as follows:

$$\begin{aligned} N_M &\leq \text{Nmax}(\text{N0} - N_Q) \\ P_M &\leq \text{Pmax}(\text{P0} - P_Q) \end{aligned} \tag{3}$$

Equation 3 imposes the restriction on the nutrient emission reductions due to measures at farms to be less than or equal to the percentage of maximum obtainable emission reduction due to measures at farms times the nutrient emissions not reduced by quota restrictions. These two inequalities are equivalent, as can be shown by combining (1) and (3):

$$\begin{aligned} N_M &\le \text{Nmax}(\text{N0} - N_Q) \Leftrightarrow \\ g_m P_M &\le \text{Nmax}(g_q \text{P0} - g_q P_Q) \Leftrightarrow \\ P_M &\le \underbrace{\text{Nmax}\frac{g_q}{g_m}}_{\text{Pmax}}(\text{P0} - P_Q) \end{aligned}$$

Hence, it suffices to use only one of both. Therefore, we add the following equation to the model:

$$N_M + \text{Nmax} \times g_q P_Q \le \text{Nmax} \times \text{N0} \tag{4}$$

The initial load to the North Sea (AeqN and AeqP) is determined by multiplying transport coefficients with initial emission levels. The N emission reductions due to measures at farms (N_M) and quota restrictions (N_Q) are multiplied by the transport coefficient for N emissions from agricultural sources (T_N). Additionally, the impact of N abatement by WWTPs (N) are multiplied by the transport coefficients for the WWTPs (T_{Ni}). The transport coefficients for P emissions can be derived analogously. Equation (5) shows this.

$$\begin{aligned} \text{AeqN} &= T_N \text{N0} + T_{Ni}\text{N0i} \\ \text{AeqP} &= T_P \text{P0} + T_{Pi}\text{P0i} \end{aligned} \tag{5}$$

In order to incorporate wetlands into the model, we calculate the nitrogen load that can by retained through wetlands $n(\text{AeqN} - T_N N_M - T_N N_Q - T_{Ni} N)$. Hence, we have to solve the following equation:

$$\begin{aligned} &T_N N_M + T_N N_Q + T_{Ni} N + n(\text{AeqN} - T_N N_M - T_N N_Q - T_{Ni} N) \\ &\quad = \text{Ntar} \times \text{AeqN} \end{aligned} \tag{6}$$

where n is the fraction of N load retained through wetlands. However, such a condition is non-linear and cannot be solved using the tools available to us. In order to get around this problem, we have used the first order Taylor expansion of $f(n) = (\text{Ntar} - n)/(1 - n)$ around Ntar instead. By substituting $\frac{\text{Ntar}-n}{1-n} \approx \frac{\text{Ntar}-n}{1-\text{Ntar}}$, we derive condition (7) from (6). The same argument can be applied on the condition for the P target.

$$\begin{aligned} &T_N N_M + T_N N_Q + T_{Ni} N + \frac{\text{AeqN}}{1-\text{Ntar}} \times n = \frac{\text{Ntar}}{1-\text{Ntar}} \times \text{AeqN} \\ &T_P P_M + T_P P_Q + T_{Pi} P + \frac{\text{AeqP}}{1-\text{Ptar}} \times p = \frac{\text{Ptar}}{1-\text{Ptar}} \times \text{AeqP} \end{aligned} \tag{7}$$

Equation (7) can be rewritten into the 5 basic variables using Equation (1), as follows:

$$\begin{aligned} &T_N N_M + T_N g_q P_Q + T_{Ni} N + \frac{\text{AeqN}}{1-\text{Ntar}} \times n = \frac{\text{Ntar}}{1-\text{Ntar}} \times \text{AeqN} \\ &\frac{T_P}{g_m} N_M + T_P P_Q + T_{Pi} P + \frac{\text{AeqP}}{1-\text{Ptar}}\frac{1}{g_w} \times n = \frac{\text{Ptar}}{1-\text{Ptar}} \times \text{AeqP} \end{aligned} \tag{8}$$

Finally, it is necessary to (naturally) restrict some of the variables in the model, in order to complete the model:

$$\begin{aligned} &N_M \ge 0; \quad P_Q \ge 0; \quad N \ge 0; \quad P \ge 0; \quad n \ge 0; \\ &P_Q \le \text{P0}; \quad N \le \text{Nmaxi} \times \text{N0i}; \\ &P \le \text{Pmaxi} \times \text{P0i}; \quad n \le \text{Nmaxw} \end{aligned} \tag{9}$$

These restrictions require nutrient abatement to be non-negative, and less than 100% of the technical constraints. There is no explicit upper boundary for N_M as this is already guaranteed by (4).

The quadratic programming model can also be written in matrix form. In that case the problem has the following shape:

$$\begin{aligned} &\min_X X^T H X - c \\ &\text{such that} \\ &AX \le b; \\ &Aeq \cdot X = beq; \\ &LB \le X \le UB \end{aligned} \tag{10}$$

Here X is the vector of nutrient emission reductions. X^T means the transpose of X. LB and UB are respectively the lower and upper bound of variable X. H is a matrix with quadratic coefficients. A is a matrix with inequality constraints, where vector b is the upper bound. Aeq is a matrix with the transport coefficients, where vector beq contains the targets of nutrient loads to the North Sea, which we want to achieve at minimum costs.

The matrices in Equation (10) have the following shape, which can be derived by combining Equations (2), (4), (8) and (9):

$$\begin{aligned} &X = \begin{bmatrix} N_M \\ P_Q \\ N \\ P \\ n \end{bmatrix}; \quad H = \begin{bmatrix} h_m & 0 & 0 & 0 & 0 \\ 0 & h_q & 0 & 0 & 0 \\ 0 & 0 & h_n & 0 & 0 \\ 0 & 0 & 0 & h_p & 0 \\ 0 & 0 & 0 & 0 & h_w \end{bmatrix}; \\ &Aeq = \begin{bmatrix} T_N & g_q \times T_N & T_{Ni} & 0 & \frac{\text{AeqN}}{1-\text{Ntar}} \\ \frac{T_P}{g_m} & T_P & 0 & T_{Pi} & \frac{\text{AeqP}}{1-\text{Ptar}} g_w \end{bmatrix}; \\ &beq = \begin{bmatrix} \frac{\text{Ntar}\times\text{AeqN}}{1-\text{Ntar}} \\ \frac{\text{Ptar}\times\text{AeqP}}{1-\text{Ptar}} \end{bmatrix}; \\ &A = [1 \quad g_q \times \text{Nmax} \quad 0 \quad 0 \quad 0]; \qquad b = \text{N0} \times \text{Nmax} \\ &LB = [0 \quad 0 \quad 0 \quad 0 \quad 0]; \\ &UB = [\infty \quad \text{P0} \quad \text{N0i} \times \text{Nmaxi} \quad \text{P0i} \times \text{Pmaxi} \quad \text{Nmaxw}] \end{aligned} \tag{11}$$

The cost minimisation problem can be solved as a quadratic programming problem with the mathematical programming language MATLAB.

From the solution, it can be verified which inequalities are binding and which are not. Once this is known, the Kuhn-Tucker (Chiang [10]) problem becomes an analytically solvable Lagrange problem, by which the optimal emission reduction for any set of transport coefficients can be calculated by a simple matrix inversion (see also [4]). Unfortunately, this closed form solution only holds for a given range of parameter values. For example, if transport coefficients would change, it is possible that other restrictions are binding and that some earlier binding restrictions are no longer binding. Then the Kuhn-Tucker problem has to be solved again to find the new set of binding restrictions.

2.1. Upscaling to Multiple Sectors and Regions

Our study applies the structure of the CF [9], which distinguishes between 10 farm types and 13 regions. Not every farm type is found in each region. Therefore, the whole Rhine basin consists of only 80, rather than 130 farm sectors. Table 3 presents the farm sectors that can be found in the various regions. Figure 1 shows the location of the regions in the Rhine river basin graphically.

Extending the model from 1 farming sector, 1 WWTP and wetlands, to the level of the entire Rhine basin, leads to 80 farming sectors where nutrients can be reduced by measures and quota restrictions (2×80). In each region there is one WWTP, which can target N and P separately (2×13). Finally there is 1 variable for the reduction in nutrient loads by the construction of wetlands (1) in the entire Rhine river basin. Hence, N_M and P_Q become both a 1×80 vector, N and P become both a 1×13 vector, while n remains one single variable. This results in 187 relevant sectors. Therefore, the whole problem can be stated in matrix form as follows:

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{187} \end{bmatrix}; \quad H = \begin{bmatrix} h_1 & \oslash & \cdots & \oslash \\ \oslash & h_2 & \cdots & \oslash \\ \vdots & \vdots & \ddots & \vdots \\ \oslash & \oslash & \cdots & h_{187} \end{bmatrix};$$

$$A = \begin{bmatrix} 1 & \cdots & \oslash & g_{q_1} \times \text{Nmax} & \cdots & \oslash & \oslash \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \oslash & \cdots & 1 & \oslash & \cdots & g_{q_{80}} \times \text{Nmax} & \underbrace{\oslash}_{27} \end{bmatrix};$$

$$b = \begin{bmatrix} \text{N0}_1 \times \text{Nmax}_1 \\ \text{N0}_2 \times \text{Nmax}_2 \\ \vdots \\ \text{N0}_{80} \times \text{Nmax}_{80} \end{bmatrix};$$

Table 3. The 80 farm sectors in the optimisation model including their index numbers.

Regions	Farm types									
	1. Cereal farms	2. General cropping farms	3. Horticulture holdings	4. Vineyard	5. Permanent crop holdings	6. Dairy farms	7. Drystock farms	8. Granivore farms	9. Mixed farms	10. Other farms
1. Switzerland+Liechtenstein		1		2	3	4	5	6	7	8
2. Austria		9		10	11	12	13	14	15	
3. Lorraine+Alsace (France)	16	17		18		19	20		21	22
4. Luxembourg				23		24	25		26	
5. Wallone (Belgium)		27	28		29	30	31	32	33	34
6. Thuringen (Germany)	35	36	37			38			39	
7. Nordrhein-Westfalen (Germany)		40	41			42	43	44	45	46
8. Hessen (Germany)		47	48			49			50	
9. Rheinland-Pfalz (Germany)	51	52		53		54			55	56
10. Baden-Wurttemberg (Germany)		57	58	59	60	61		62	63	64
11. Bayern (Germany)		65	66			67	68	69	70	
12. The Netherlands		71	72		73	74	75	76	77	
13. Saarland (Germany)						78			79	80

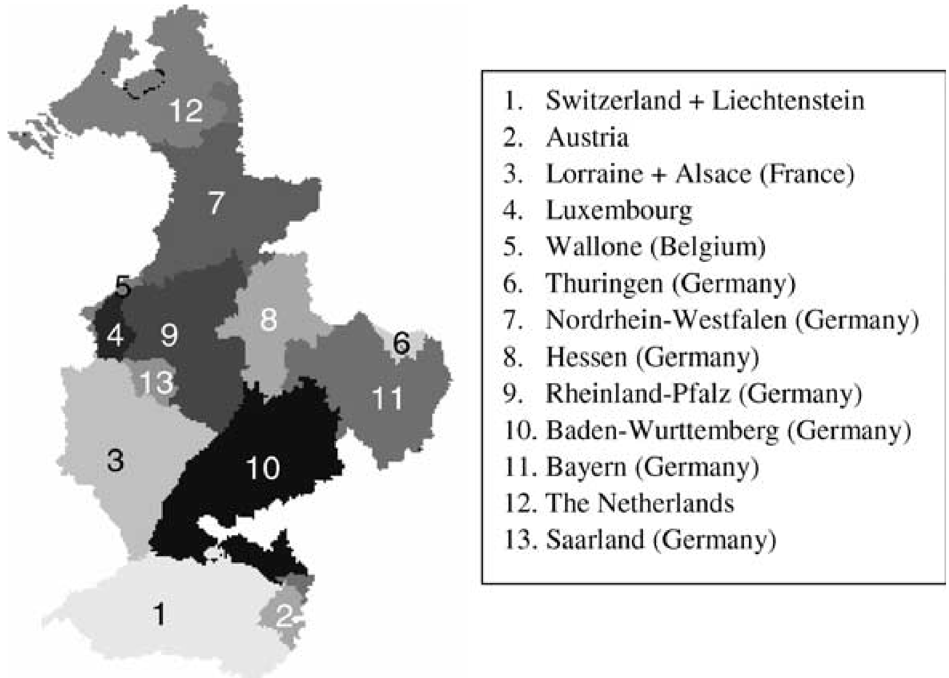

Fig. 1. Overview of the source regions considered within the Rhine basin.

$$
\begin{aligned}
Aeq &= \begin{bmatrix} Aeq_{1,1} & Aeq_{1,2} & \cdots & Aeq_{1,186} & \frac{\text{AeqN}}{1-\text{Ntar}} \\ Aeq_{2,1} & Aeq_{2,2} & \cdots & Aeq_{2,186} & \frac{\text{AeqP}}{1-\text{Ptar}} g_w \end{bmatrix}; \\
beq &= \begin{bmatrix} \frac{\text{Ntar}\times\text{AeqN}}{1-\text{Ntar}} \\ \frac{\text{Ptar}\times\text{AeqP}}{1-\text{Ptar}} \end{bmatrix}; \\
LB &= \underbrace{[0 \quad 0 \quad \cdots \quad 0]}_{187}^{T}; \\
UB &= [UB_1 \quad UB_2 \quad \cdots \quad UB_{187}]^{T}
\end{aligned} \tag{12}
$$

With the expanded matrices above (H is a 187×187 matrix) the so-called bordered Hessian can be built (Equation (13)). This bordered Hessian is the solution of the Lagrangian problem, where the vectors in the borders contain only those constraints that are binding and all other constraints are eliminated from the model. This is exactly what the MATLAB quadratic programming model does, namely, trying to find iteration-wise the binding equations, searching for the solution.

$$
\begin{aligned}
&\begin{bmatrix} H & -Aeq^{T} & A(1)^{T} \\ -Aeq & \oslash & \oslash \\ A(1) & \oslash & \oslash \end{bmatrix} \begin{bmatrix} X \\ \lambda \\ \mu \end{bmatrix} = \begin{bmatrix} \oslash \\ -beq \\ -b(1) \end{bmatrix} \Leftrightarrow \\
&BY = g \Leftrightarrow Y^{\text{opt}} = B^{-1} g
\end{aligned} \tag{13}
$$

Where $\lambda = [\lambda_N \;\; \lambda_P]^T$ and $\mu = [\mu_1]$; $A(1)$ and $-b(1)$ contain the binding restrictions.

3. CALIBRATING THE OPTIMISATION MODEL

3.1. The Data

The input data for the optimisation model are generated with the computational framework (CF). This CF is a dynamic simulation model with yearly steps, with 1990 as base year and 2015 as target year. The CF consists of 7 modules modeling nutrient emissions (1), nutrient transport (2), river and lake water quality (3), and assessing environmental quality (4), economic impact (5), costs (6), and sustainability (7). The CF is calibrated towards the European renaissance scenario, which is taken from the CPB (Otto et al. [8]; RIZA and RIKZ [11]; EEA [12]) for the baseline calculations. Further details on the CF can be found in Tanczos [9].

The output of the CF consists of detailed information about the 80 agricultural sectors and a number of exclusive measure packages for each agricultural sector. The output of the CF contains the annual costs of implementation and the impact expressed in nutrient abatement for each measure in each farm sector. These data, however, are not immediately in the right format, but have to be processed first with a number of software packages.

Besides the detailed data at the sectoral level, the CF also delivers important indicators at the Rhine river basin level. It provides, for example, an estimate for the costs of constructing wetlands in the Rhine river basin and information about the emissions from WWTPs. This refers to a situation in which maximally 10% of the riverbanks are used as retention wetlands. Since the opportunities for the creation of wetlands are limited in large areas in the Rhine basin, due to, for example, urbanisation or other vested interests, wetlands can only be created to a limited extent.

3.2. Interaction Between Software Packages

The software packages shown in Figure 2 interact as follows. The output of the CF, emission levels for N and P and costs for 80 farming sectors and a number of measure packages, is stored in an EXCEL spreadsheet to calculate the percentages of N and P reduction. Furthermore, a joint N and P reduction percentage is calculated using euthrophication units, where 1 million kg P is one unit and 10 million kg N is equal to one euthrophication unit [6]. This method is only used to order the measures; this kind of integration in not used in the optimisation model. The cost effectiveness of a measure package in a particular farming sector is calculated using the following formula:

$$\mathrm{CE}_i = \frac{\mathrm{Cost}_i}{\mathrm{NPred}_i} \tag{14}$$

Where CE_i is the cost effectiveness of measure i, Cost_i is the cost of fully implementing measure i, while NPred_i is the sum of the total attainable reduction of P and N (described in eutrophication units). Consecutively all information on (1) N, (2) P and (3) N&P reduction, (4) measure number, (5) costs and (6) CE is gathered in one EXCEL spreadsheet. A programme in Visual Basic for Applications (VBA) is used to join the above mentioned 6 variables per farming sector. After that, the program orders the measures according to their cost effectiveness. Finally, the program selects all measures that can reduce nutrient emissions at least cost. All other measures are excluded. This leads to a list of cost effective measures for each farming sector.

This list of cost effective measures still contains measures which can reduce nutrients at negative cost. In our analysis, we consider 'a rational agent,' who has already taken the measure with the highest N&P reduction potential at a negative cost in the initial optimal situation. This can be realised by subtracting the costs and effects of the measure with highest nutrient reduction at negative cost from the costs and effects of the remaining measures for each farm sector (Table AI.1 gives an overview of these measures for all farming sectors). In this way, we consider costs and effects of the remaining measures relative to the initial optimal situation (for a rational agent).

In applying the assumption of 'a rational agent,' it is possible to reduce 8.5% N and 4.7% P and save 63.1 million € ($= c$ in Equation (2)) in the agricultural sector in the optimal initial situation. This is equal to a load reduction of 2.7% N and 0.3% P to the North Sea. The sectoral levels of emission reduction percentages, the measure number, the costs and cost effectiveness in the initial (optimal) situation are given in Table AI.1 in the Appendix. Table AI.2 gives the meaning of measure numbers in Table AI.1.

The above derived list of cost-effective measures is used as input into a program in Turbo Pascal to generate 100 data points for costs, N emissions and P emissions, for each of the 80 agricultural sectors. These 100 data points are constructed in such a way that the most cost effective measure is exhausted for 100%, then the curve jumps to the second most cost effective measure and so on. Figure 3 illustrates this. This process starts from 0% and continues with steps of 1% until 100% of the maximum attainable emission reduction with measures at farms.

The data set generated with Turbo Pascal is then used for a regression analysis to estimate the linear quadratic cost

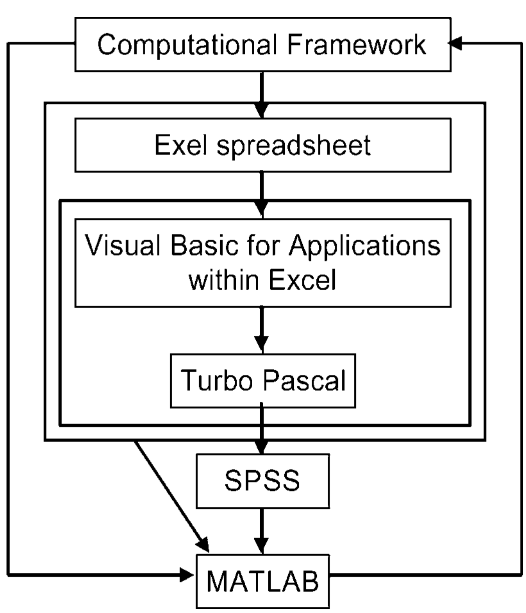

Fig. 2. The interaction between software packages.

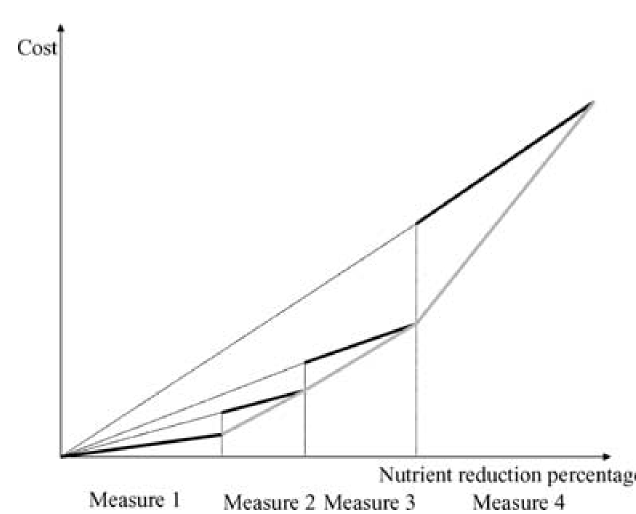

Fig. 3. The actual shape of the cost effectiveness curves.

Table 4. Number of hectares of arable farming, cows, sows, feeding pigs and inhabitant equivalents for the various regions in the Rhine river basin [21].

Region (x1000)	Poultry	Arable land (km^2)	Dairy cows	Breeding pigs	Feeding pigs	Inhabitant equivalent
1. Switzerland+Liechtenstein	5734	282	776	220	660	7590
2. Austria	190	3	29	6	3	425
3. Lorraine+Alsace (France)	2589	672	420	30	93	5301
4. Luxembourg	60	57	76	13	16	546
5. Wallone (Belgium)	53	5	17	0	0	99
6. Thuringen (Germany)	9	19	8	2	4	67
7. Nordrhein-Westfalen (Germany)	3961	585	373	316	1079	19154
8. Hessen (Germany)	1382	271	140	55	199	6477
9. Rheinland-Pfalz (Germany)	1093	412	225	73	225	5488
10. Baden-Wurttemberg (Germany)	3020	651	495	209	474	12428
11. Bayern (Germany)	1744	675	403	134	459	5358
12. The Netherlands	38922	392	1220	519	1355	13285
13. Saarland (Germany)	216	38	26	5	16	1495
Total	58973	4062	4206	1583	4582	77714

functions for reducing N by measures ($\mathrm{Cost}(N_M) = h_m N_M^2$). In 8 cases (Sectors 6, 14, 29, 62, 69, 71, 72, 73) we do not find any measures with positive cost to reduce N&P. In that case we substitute for h_m an arbitrarily small value (eps $= 10^{-8}$) and restrict this variable from above by 'eps.' Otherwise the optimisation model cannot be solved, as the model cannot find a variable in the interval [0, 0].

In 5 cases (Sectors 28, 41, 66, 76, 77) we find a possibility to reduce N and P simultaneously. This is three times on horticultural farms (28, 41, 66) and two times in the Netherlands (76, 77). In those cases we introduce dependence between N and P through a non-negative g_m (Equation (1)). The relation between N and P is approximated using a linear relation. In case no measures exist to reduce P, the term T_p/g_m in Aeq in Equation (11) becomes zero. The Netherlands is the only region where substantial P reductions are attainable through measures: up to 35%. In all other regions the maximum attainable P reduction through measures is less than 0.5%. This is caused by the fact that most pig farms in the Rhine river basin are in the Netherlands (see also Table 4).

The calculation of the quadratic estimates for the quota restrictions on farms can be done straightforward by generating 100 data points from the initial nutrient emissions of the farm and the total value of the farm. These data are also provided by the CF. SPSS is used to estimate '$\mathrm{Cost}(P_Q) = h_q P_Q^2$.' In this case it is always costly to close a farm. As explained before, for quota restrictions we take a linear dependence between N and P. The estimated parameters, the initial emissions and the maximum emission reductions possible for N and P are presented in Table AI.3 in Appendix I. Nutrient abatement by WWTPs is also calibrated using data from the CF. The CF provides the costs and effects of emission reduction with respect to the baseline. The output of the CF shows that this effect is linear. At the baseline, a part of the population is already linked to secondary treatment. The annual costs to fully link them to tertiary wastewater treatment are estimated. As before with quota restrictions, 100 data points are generated. These are fed into SPSS and a quadratic link is fitted. The quadratic term is input into the model.

However, in approximating a linear relation by a quadratic function, the (marginal) costs of low emission reduction percentages are lower. In the cost-effective allocation this may result in higher nutrient abatement percentages (1–2%) in the lower ranges than in case of a linear relation (0%). This applies to all linear relations that have been estimated with quadratic cost functions (quota restrictions in agriculture, and some measures in both agriculture and WWTPs). The estimated values of the parameters are presented in Table AI.4 in Appendix I.

Wetlands comprise one sector in the model. As before, 100 data points are generated. This was done using 4 fractions of wetlands in the Rhine river basin, respectively 1.1%, 2%, 4.4% and 10%. The results of the parameters of the model for wetlands are presented in Table AI.5 in Appendix I.

The reduction percentages per measures and quota restrictions in Table AII.1 are difficult to calculate, because we need to correct for the emissions reduced by closing down a percentage of the farms in a particular sector. This is done with the following formulas:

$$\mathrm{Nmeas} = \begin{cases} 100 \times \frac{N_M}{\mathrm{N0} - g_q \times P_Q} & \text{as long as N0} > g_q \times P_Q \\ 0 & \text{otherwise} \end{cases};$$

$$\mathrm{Pquota} = \begin{cases} 100 \times \frac{P_Q}{\mathrm{P0}} & \text{If N and P are reduced independently} \\ 100 \times \frac{P_Q}{\mathrm{P0} - N_M/g_m} & \text{as long as P0} > N_M/g_m \text{ and if N and P are mutually dependent} \\ 0 & \text{otherwise} \end{cases}$$

4. RESULTS AND SENSITIVITY ANALYSIS

4.1. Results

A shift from flat rate emission reduction policies towards a cost-effective allocation can only be beneficial if certain emitters are more cost-effective in reducing nutrient loads to the North Sea than other sources. One of the causes of the variation in cost-effectiveness is the difference in impacts of abatement by the various nutrient-emitting sources on the loads to the North Sea, as described by the transport coefficients (presented in Table 5). Regions with high transport coefficients have a more significant impact on the nutrient load to the North Sea than regions with low transport coefficients. If cost functions would be the same for the various sectors in the various regions, the activities located in regions with high transport coefficients would have to reduce their emissions to a larger extent than activities in regions with limited impact on the North Sea. This is why [4] found that regions with relatively high transport coefficients also have relatively high emission reduction percentages.

However, this result is not found in this study, as can be concluded from Figure 4, which shows the N emission reduction in the various regions and distinguishes between N reduction by measures and quota restrictions at farms and N reduction by WWTPs, together with the transport coefficients (the transport coefficients are multiplied by 100 to be able to plot them in the same figure). This is mainly because different cost functions are used for the various sectors in

Table 5. Transport coefficients used in the base run and sensitivity analyses.

	Farm level				Waste water treatment plants					
	Nitrogen (T_N)			Phosphorus Mean (T_P)	Nitrogen (T_{Ni})			Phosphorus (T_{Pi})		
	Min	Mean	Max		Min	Mean	Max	Min	Mean	Max
1	0.1435	0.3229	0.5292	0.0092	0.6672	0.9481	1.0000	0.6040	0.7190	0.9587
2	0.0936	0.2952	0.5449	0.0026	0.5547	0.7384	0.8214	0.0636	0.1695	0.3301
3	0.0497	0.1987	0.3477	0.0044	0.5321	0.8294	0.9546	0.2035	0.6377	1.0000
4	0.0916	0.3357	0.5798	0.0089	0.5590	0.8808	1.0000	0.2327	0.6690	1.0000
5	0.0727	0.2665	0.4603	0.0053	0.5466	0.7277	0.8095	0.1538	0.4098	0.7980
6	0.0647	0.2042	0.3769	0.0041	0.5126	0.6824	0.7591	0.1206	0.3212	0.6255
7	0.0652	0.1739	0.3478	0.0041	0.6585	0.7761	0.8349	0.1969	0.5286	1.0000
8	0.0619	0.2268	0.4742	0.0050	0.6708	0.8706	0.9562	0.1651	0.6004	1.0000
9	0.0497	0.2319	0.4638	0.0059	0.6153	0.7986	0.8772	0.1284	0.6294	1.0000
10	0.0520	0.2425	0.5023	0.0055	0.5992	0.8389	0.9438	0.1457	0.6165	1.0000
11	0.0844	0.1970	0.0138	0.0043	0.5875	0.7703	0.4545	0.2374	0.5934	0.1484
12	0.0165	0.0434	0.0703	0.0092	0.1463	0.1600	0.1669	0.0406	0.1060	0.2255
13	0.0896	0.2827	0.5218	0.0070	0.6604	0.8791	0.9779	0.2639	0.7031	1.0000

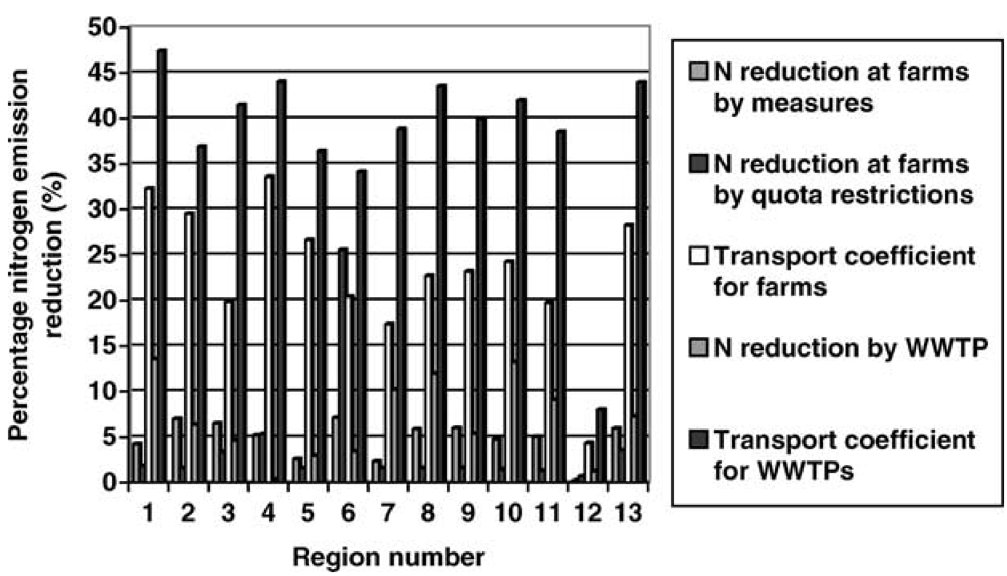

Fig. 4. Percentage N emission reduction in the various regions in a cost-effective allocation. Target is a 30% reduction in nutrient loads to the North Sea (for region numbers, see Table 3). Also the transport coefficients are represented (for agricultural sources multiplied by 100, for WWTPs by 50).

various regions. Figure 4 also shows that quota restrictions are of limited importance for most regions, while a quarter of the farms in Thuringen (Region 6) has to be closed to be able to reduce nutrient loads to the North Sea at least costs. The first column in Table AII.1 in appendix II contains the detailed sectoral optimal emission reduction percentages, when both N and P loads to the North Sea have to be reduced by 30%.

Figure 5 presents the cost-effective P abatement in the various regions, together with the transport coefficients. This figure shows P reduction through measures at farms, P reduction through quota restrictions, and P reduction by WWTPs. Again the agricultural sector in Thuringen (Region 6) has to reduce their emissions to a far larger extent than its counterpart in other regions, despite the fact that the transport coefficient is not significantly higher than for the other regions. Apparently the abatement costs are lower for this region.

Figure 6 shows the differences in N reduction through measures at farms, P reduction through quota restrictions and total P reduction for the 10 farm types considered and the WWTPs. For most agricultural sectors a reduction in

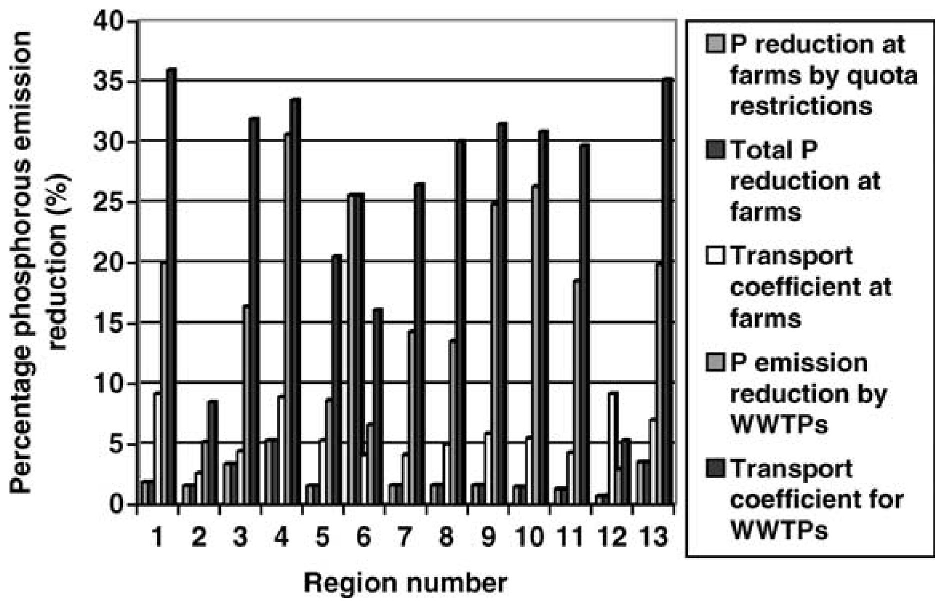

Fig. 5. Percentage P emission reduction in the various regions in a cost-effective allocation. Target is a 30% reduction in nutrient loads to the North Sea (for region numbers, see Table 3). Also the transport coefficients are represented (for agricultural sources multiplied by 1,000, for WWTPs by 50).

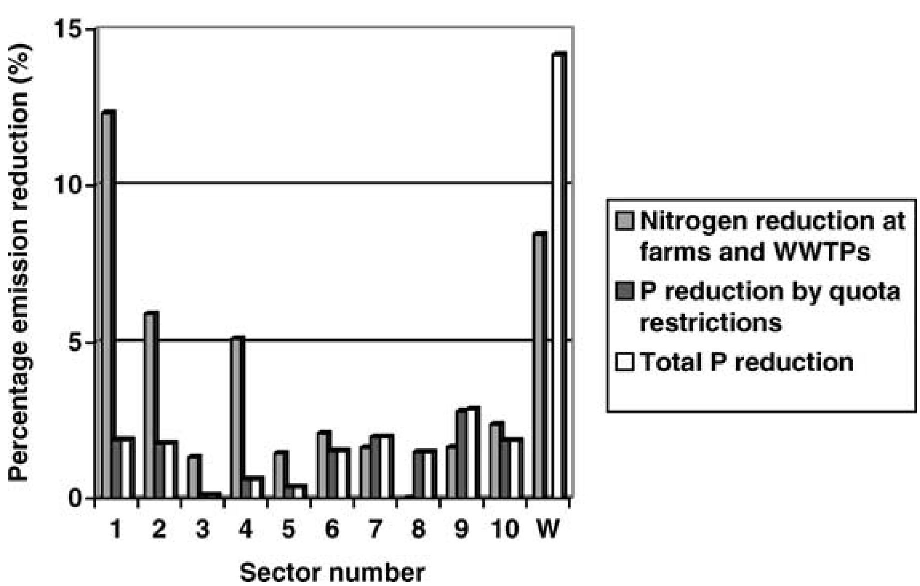

Fig. 6. Percentage N and P emission reduction and farm closures by various agricultural sectors in a cost-effective allocation of 30% reduction in loads to the North Sea (for sector numbers, see Table 3; W = WWTP).

production capacity is the only possibility to reduce P emissions. Only for mixed farms (Sector 9) total P abatement is slightly more than P reduction by quota restrictions. Apparently, they will have to apply some measures at farms to reduce P emissions.

Cereal farms (Sector 1), general cropping farms (Sector 2), vineyards (Sector 4), and WWTPs will have to apply measures to reduce N emissions in the cost-effective allocation. However, these abatement percentages are modest compared to those presented by Van der Veeren and Tol [4]. This is because, in the present analyses, large amounts of nutrients are captured by nutrient retention in wetlands, a possibility not considered by Van der Veeren and Tol [4].

WWTPs are relatively cost-effective with respect to nutrient abatement. Therefore, they would, in a cost-effective allocation, be encouraged to increase abatement activities. However, in some regions their abatement opportunities are restricted by technological constraints.

4.2. Sensitivity Analyses

A number of assumptions underlying the model will be perturbed one by one and the impacts will be compared to the results presented in the previous subsection. First of all, transport coefficients depend on weather conditions and are, therefore, different for dry and wet years. This can have impacts on the cost-effective allocation of nutrient emissions and related costs. Secondly, technological development may alleviate technical constraints, and reduce the relevancy of quota restrictions (and thus reduce costs). This applies to WWTPs, but also to measures that can be applied by agriculture. Thirdly, the assimilative capacity of wetlands to absorb nutrients may be overestimated in the previous analyses. Not only the assimilative capacity, but also the costs of wetlands are rather uncertain. Therefore the results will also be tested on their sensitivity for higher costs for wetlands. Table 6 summarises the main characteristics of the 11 considered alternatives.

4.2.1. Transport Coefficients

Hydrological variations have important consequences on run-off, discharge, and retention. Table 5 presents the ranges for the nutrient transport coefficients used in the sensitivity analyses. The minimum and maximum values are calculated (percentage-wise), based on ranges described by Schuttelaar [14]. The coefficients used in the previous analyses are presented in Table 5 as ‘‘mean’’ values.

In general, it can be expected that during humid years, more nutrients run off, and therefore, agricultural nutrient management may become more important. Figure 7 indeed shows that agricultural nutrient abatement becomes relatively more important as hydrological circumstances relate more to a year with high rainfall. This result could already be predicted by comparing the upper and lower bounds of the transport coefficients. For WWTPs they differ less than 100%, whereas for agricultural sources, the coefficients can be almost ten times as high (note that for P emissions from agricultural sources the transport coefficients are assumed to be identical, for dry, mean, and humid years). A peculiar result is that N abatement by WWTPs decreases in wet and dry years, compared to the base situation. This is caused by differences in cost effectiveness between measures at farms and WWTPs. The switch from secondary to tertiary purification at WWTPs is, apparently, relatively more expensive than measures at the farm level.

4.2.2. Technological Development

The previous analyses showed that in the cost-effective allocation of nutrient abatement measures in some regions (especially in Thuringen) farms have to be closed. The implementation of quota restrictions may however be prevented by technological development. For example, over the past decade, much research activities were aimed at technoogical development in nutrient abatement at WWTPs (see, for example, Meinema and Rienks [15]; STOWA [16, 17]; Rijsdijk [18]; Senhorst [19]; Warmer [20]; Ewijk [21]). These research activities increased the number of

Table 6. Costs for the various alternatives (in Million Euros per year).

Alternatives	Description	Costs (M€/year)
Base case	Base run with the model	286.8
Dry year	Minimum values for transport coefficients	291.4
Wet year	Maximum values for transport coefficients	282.3
Cheap wetlands	Construction of wetlands 5 times cheaper ($h_w/5$)	38.2
Expensive wetlands	Construction of wetlands 5 times more expensive (h_w*5)	949.9
Low retention wetlands	Reduction capacity of wetlands 3 times less (Nmaxw/3)	1784.8
Cheap measures	Measures at farms and waste water treatment plants twice cheaper ($h_m/2$, $h_n/2$, $h_p/2$)	217.9
Low reduction	Reduction capacity with measures at farms and waste water treatment plants twice lower (Nmax/2, Nmaxi/2, Pmaxi/2)	338.8
50% N load	Reduction target of 33.1% N load reduction, P load free	290.0
70% N load	Reduction target of 59.8% N load reduction, P load free	1456.1
70% N and 75% P load	Reduction target of 59.8% N and 42.8% P load reduction	1484.9

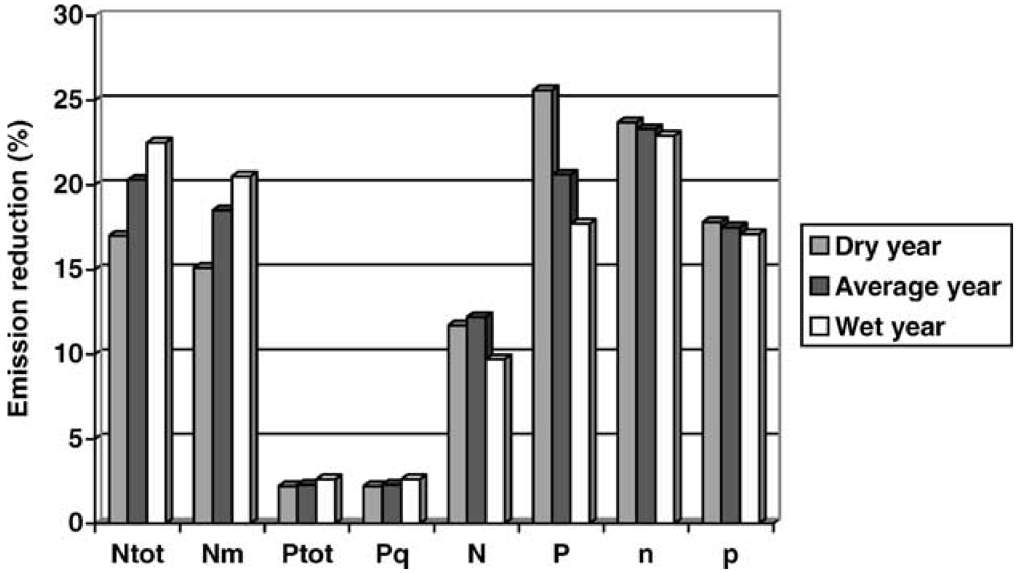

Fig. 7. The impacts of changes in transport coefficients on nutrient abatement measures in the Rhine basin in a cost-effective allocation of 30% reduction in loads to the North Sea for dry average and wet years.

technological options and showed what is technologically feasible. However, most of these research activities were pilot projects and therefore costs are relatively uncertain.

Technological development can be included in the present analysis by assuming that cost curves can be extrapolated to represent cost reduction due to new technologies. It turns out that a reduction of the abatement costs at farms and WWTPs leads to a shift of nutrient retention by wetlands to substantial increases of measures at WWTPs and to a lesser extent at farms. It also reduces the total cost of reaching the joint 30% nutrient reduction target. If, on the other hand, the reduction potential of measures at farms and WWTPs would decrease by 50% (''technological retardation''), technological constraints become binding, as can be seen in Figure 8 by the significant decreases in N_M, N and P. Reduced nutrient abatement by measures appears to be more than compensated by increased nutrient retention by wetlands. This means that, if technical constraints are tightened, less quota restrictions are applied, but more nutrient retention by wetlands has to take place.

Technological development can not only increase the technical constraints, but it may (also) decrease costs of measures. It appears that if measures become less expensive, they will be implemented to a larger extent. At the same time

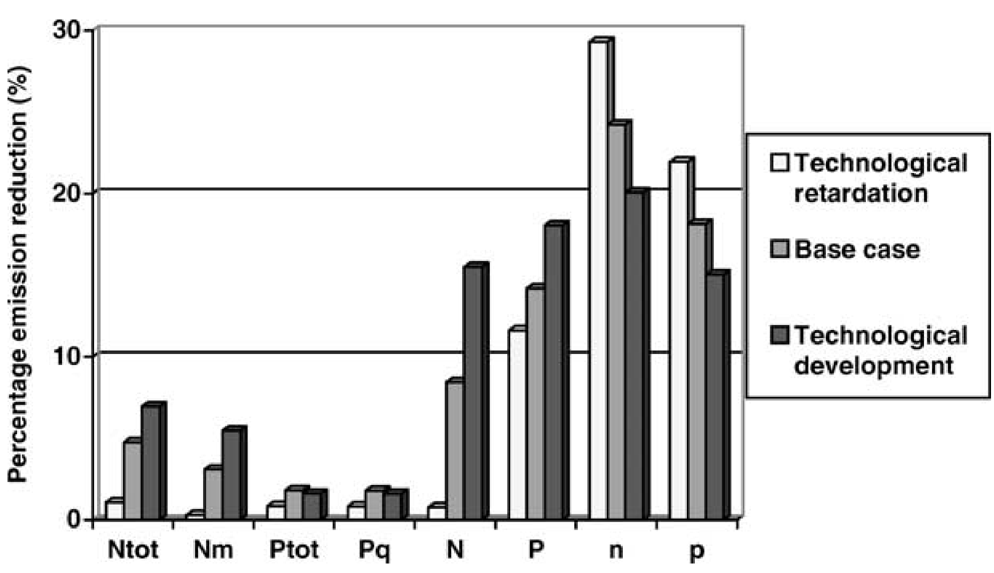

Fig. 8. The impacts of changes in technological development on nutrient abatement measures in the Rhine basin in a cost-effective allocation of 30% reduction in loads to the North Sea.

quota restrictions and wetlands become less important in the cost-effective allocation of nutrient abatement options.

4.2.3. Wetlands
In the following analyses, special attention is paid to the role of wetlands. First, because the assimilative capacity of wetlands to absorb nutrients is uncertain in the base case, and secondly, because the costs of constructing wetlands are uncertain [9].

Figure 9 presents the results in case the maximum assimilative capacity is assumed to be 33% of the maximum capacity assumed previously. The figure also shows the results in case the wetlands are 5 times more and 5 times less expensive. These results are depicted against the base results presented in the previous sub-sections.

Figure 9 shows that, if the nutrient absorbing capacity of wetlands would be less than assumed in the base case, agricultural sources and WWTPs will have to reduce their nutrient emissions to a larger extent. However, since the increase in P abatement at WWTPs is limited due to technical constraints, P emission reductions mainly have to take place in agriculture. Because most agricultural activities already exploit their P abatement options to their full extent, there are no other options left than to reduce the number of farms. By doing so, not only P emissions, but also N emissions are reduced. It appears that these quota restrictions reduce N loads to a sufficient degree, such that WWTPs do not have to increase their N abatement activities when wetlands would be less effective than previously assumed.

A largely similar story applies to changes in the costs for creating wetlands. If nutrient abatement by creating wetlands becomes more expensive than in the base case, nutrient abatement by agricultural sources and WWTPs becomes more important.

4.3. Costs of Nutrient Abatement

A comparison of the costs for the various nutrient abatement alternatives shows that a cost-effective allocation of nutrient abatement measures is more expensive for dry years than for wet years. As we saw, nutrient abatement by agricultural sources becomes more important in wet years. Apparently, these measures are less expensive than the measures that have to be applied by WWTPs in dry years. However the difference in costs are not very large, while the variation in the transport coefficients is quite large.

The total costs for nutrient abatement in the Rhine basin decrease considerably as creating wetlands becomes less expensive ($h_w/5$) and increase considerably as wetlands become more expensive (h_w*5). This result shows that the total nutrient abatement costs for the Rhine basin are quite sensitive to perturbations in the cost estimate of wetlands, which is quite uncertain in our model.

It appears that the increase in P abatement by agricultural sources, in case the nutrient absorbing capacity of wetlands is less than previously assumed, results in a significant increase in total abatement costs. This is caused by an increase in relatively expensive quota restrictions.

Technological development may decrease the costs for measures at farms and WWTPs ($h_t/2$, $h_n/2$, and $h_p/2$). However, since in the optimal allocation of nutrient abatement measures the nutrient retention by wetlands is more important than the nutrient abatement by measures, a change in costs for measures can be expected to be less relevant than changes in costs for wetlands. This is also why a significant decrease in options for nutrient abatement by agricultural sources and WWTPs (Nmax/2, Nmaxi/2, Pmaxi/2) does not result in a significant increase in the

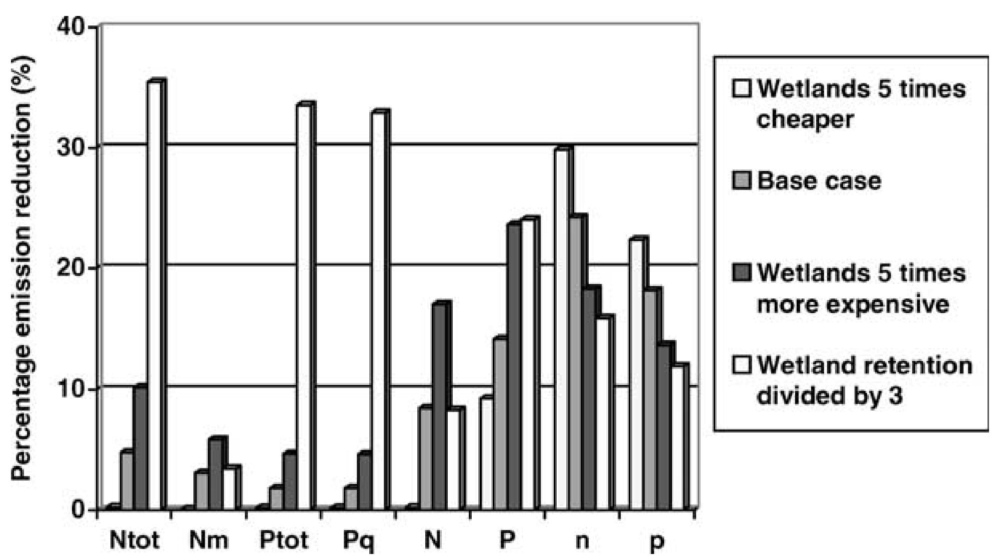

Fig. 9. Nutrient abatement measures in the Rhine basin in a cost-effective allocation of 30% reduction in loads to the North Sea if the capacity of wetlands to absorb nutrients would be 67% less than previously assumed, the creation of wetlands would be 5 times less expensive, or 5 times more expensive.

total costs of a cost-effective allocation of nutrient abatement in the Rhine basin.

4.4. Policy Alternatives

The model can also be used to calculate the impact of current polices. It is well-known from the OSPAR agreement and the North Sea conference that the load of N and P to the North Sea with respect to 1985 levels should be reduced by 50% in the short run (50/50) and 70% N and 75% P in the long run (70/75). As mentioned in the introduction, in the baseline of the CF, a load reduction will be achieved of 25.3% N and 56.3% P by 2015. This means that, in order to achieve the 50/50 target, it is not necessary to reduce any P. This can be accommodated by the model by only reducing N emissions. Then, WWTPs would obviously no longer apply P abatement measures in the cost-effective situation.

Since wetlands absorb both nutrients at the same time, a reduction in P retention requires additional N abatement by WWTPs and agriculture. Agricultural sectors, therefore, have to apply more quota restrictions, also if only N loads have to be reduced. In order to achieve the 50/50 target, 33.1% N load has to be reduced with respect to the baseline. This will cost 290.0 million € and results in a further reduction of P with 24.6%, which is equal to a P load reduction of 67.1% with respect to base year 1985.

Two additional alternatives are considered here, namely the case where the target of a 70% N load reduction is achieved. This is possible for 1456 million €, while an additional 38.7% P load is reduced as well, which is equal to a P load reduction of 73.2% with respect to base year 1985. In the final alternative the 70/75 target is achieved. Then the model estimates a total annual cost of 1485 million €.

5. CONCLUSIONS

Flat rate emission reduction policies are easy to formulate, since they do not require a thorough analysis of (marginal) nutrient abatement costs, as is the case with cost-effectiveness analysis. In addition, a flat rate policy may sound fair, because everybody has to reduce by the same percentage. However, the same objective (expressed in terms of reductions in nutrient loads) can be achieved at significantly lower costs, if emission reductions are allocated in a cost-effective way. Such a cost-effective allocation does, however, require the use of sophisticated models, such as the model presented in this paper, which can calculate the cost-effective joint N and P emission reduction in the Rhine river basin, given a desired N and P load into the North Sea.

As a solution of the model, the cost-effective allocation of nutrient abatement measures in the Rhine basin is mainly achieved by constructing wetlands for nutrient retention. Apparently, nutrient retention by the creation of wetlands reduces nutrient loads at lower costs than abatement measures at agricultural sectors and WWTPs. However, data for wetlands, on both costs and retention, are quite uncertain. The sensitivity analysis of this paper shows that, if wetlands would be more expensive, the abatement costs for the entire Rhine basin would increase substantially. The reason for this cost increase is that, since less nutrient retention by wetlands takes place, more nutrient abatement has to be obtained from other sources. If, in such a situation, WWTPs would not be able to increase their technological options to reduce P emissions, a larger fraction of farms would have to be closed. However, over the past decades, technological developments have taken place especially in WWTPs, which resulted in increasing nutrient reduction potentials and decreasing costs. From a cost-effectiveness point of view, it is highly interesting that these developments take place in this particular sector. Technological development in agriculture does not reduce the necessity of quota restrictions in the case of a joint N and P load reduction target, as the majority of measures can only be targeted at nitrogen. At best a trade off between measures at farms and WWTPs can be observed in such a situation. This hardly reduces the need for constructing wetlands, as the P load is the limiting factor in the case of a joint N and P load reduction to the North Sea.

Differences between agricultural sectors are especially important with respect to their possible options to reduce N emissions with measures. It appears that only cereal farms, general cropping farms, and vineyards will have to apply N abatement measures for more than 5%. For all agricultural sectors (except mixed farms), the only option to reduce P emissions is by quota restrictions. In the cost-effective allocation all sectors will have to be reduced to a limited extent. However there are large differences between the various regions. For example, in the optimal situation the model suggests to close more than 10% of the general cropping farms, dairy farms, and mixed farms in Thuringen, whereas in most other regions this is less than 2%. The latter may be due to the fact that the model uses a quadratic approximation for a linear relation. This implies that for small emission reduction percentages the (marginal) costs are relatively low, and thus the cost-effective outcome may require some quota restrictions, whereas if linear cost functions would have been used, no quota restrictions would be required.

Differences between regions with respect to agricultural nutrient abatement are small, except for the relatively high percentage of farms that has to be closed in Thuringen. The regional differences are more important for nutrient abatement by WWTPs. For example, P abatement by WWTPs is more than 20% in Luxembourg, Rheinland-Pfalz, and Baden-Wurttemberg, but less than 5% in the Netherlands, where the transport coefficients are substantially lower.

As could be expected, agricultural nutrient abatement becomes more important in wet years than in dry years. This means that weather conditions have serious impacts on the optimal (cost-effective) allocation of nutrient emissions, however, the costs are largely similar.

Future research should aim at re-calibrating the optimisation model with region specific information about abatement cost curves, not only for measures, but also for quota restrictions, both at the farm level and the industrial level.

The result of the optimisation model in this paper shows the complexity of treating many sectors together with a multiple target function in an optimisation framework. Furthermore, we have also shown how wetlands can be included into the optimisation model. Future research on costs and reduction capacities of wetlands promises to be a fruitful exercise.

ACKNOWLEDGEMENTS

We appreciate the collaboration with the simulation team from Delft Hydraulics. Discussions with Ilka Tanczos and Annette Kuin have been valuable. The regular meetings in the Sustainability and environmental Quality in transboundary River basins (SQR) project has led to various improvements in the paper. Comments are appreciated from participants in presentations in 2001 of this paper in CSERGE, Norwich, UK, April 23–24; GKSS, Geesthacht, Germany, June 21–22 and during the 4th open science meeting of European Land-Ocean Interaction Studies (ELOISE), Rende, Italy, 5–7 September. Finally, we thank Richard Tol and two anonymous referees of this journal for comments on earlier drafts of this paper. Funding from the Dutch organisation for research (NWO) to complete the SQR project and funding from the EU (contract number ENV1-2000-00044) for the EUROCAT project are gratefully acknowledged. Any remaining errors are ours.

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APPENDIX I. ESTIMATED PARAMETERS OF THE MODEL.

Table AI.1. The optimal initial situation, where the options to reduce nutrient emissions at negative cost is maximised.

Sector	%N&P	%N	%P	Measure number	Cost (M€)	CE
1	0.73	3.02	0.00	5	0	0
2	0.82	3.15	0.00	5	0	0
3	1.09	4.01	0.00	18	−0.023	−0.021
4	0.30	0.80	0.00	1	0	0
5	1.09	2.98	0.00	5	0	0
6	4.78	10.66	1.46	9	−0.176	−0.037
7	0.77	2.66	0.00	5	0	0
8	2.51	8.22	0.00	5	0	0
9	0.68	2.97	0.00	5	0	0
10	0.76	3.11	0.00	5	0	0
11	0.76	2.94	0.00	18	−0.001	−0.002
12	0.07	0.19	0.00	4	0	0
13	1.03	2.93	0.00	5	0	0
14	4.81	10.96	1.46	9	0	0
15	0.72	2.59	0.00	5	0	0
16	0.27	1.15	0.00	5	0	0
17	0.27	1.11	0.00	5	0	0
18	0.32	1.31	0.00	5	0	0
19	1.22	5.18	0.00	4	0	0
20	1.31	5.00	0.00	4	0	0
21	0.34	1.47	0.00	5	0	0
22	0.40	1.34	0.00	5	0	0
23	1.73	4.49	0.00	5	0	0
24	0.09	0.23	0.00	1	0	0
25	2.66	6.61	0.00	5	0	0
26	2.67	7.35	0.00	5	0	0
27	1.21	5.50	0.00	5	0	0
28	1.58	6.52	0.00	5	0	0
29	0.63	2.44	0.02	16	−0.0001	−0.0002
30	0.52	1.26	0.00	4	0	0
31	1.49	3.61	0.00	5	0	0
32	1.45	4.26	0.00	9	−0.003	−0.002
33	1.06	2.93	0.00	5	0	0
34	1.67	6.85	0.00	5	0	0
35	0.34	1.56	0.00	15	−0.0003	−0.0008
36	0.36	1.16	0.00	9	−0.025	−0.069
37	0.58	2.27	0.00	18	0	0
38	0.35	1.22	0.00	4	0	0
39	0.38	1.12	0.00	9	−0.053	−0.141
40	0.84	3.71	0.00	5	−0.002	−0.003
41	0.95	3.42	0.00	5	−0.0001	−0.0001
42	0.33	0.81	0.00	1	0	0
43	1.10	2.86	0.00	5	0	0
44	2.13	5.97	0.00	9	−0.053	−0.025
45	2.74	6.53	0.00	9	−1.361	−0.497
46	0.83	3.00	0.00	5	−0.001	−0.002
47	0.52	2.38	0.00	5	0	0
48	0.47	1.87	0.00	5	0	0
49	0.20	0.56	0.00	1	0	0
50	0.55	2.05	0.00	5	0	0
51	0.67	3.12	0.00	5	0	0
52	0.53	2.58	0.00	5	0	0
53	0.53	2.23	0.00	5	0	0
54	0.17	0.45	0.00	1	0	0
55	0.67	2.58	0.00	5	0	0

Table AI.1. (*continued*)

Sector	%N&P	%N	%P	Measure number	Cost (M€)	CE
56	0.40	1.14	0.00	5	0	0
57	0.94	4.38	0.00	5	0	0
58	0.90	3.39	0.00	5	0	0
59	0.92	3.71	0.00	5	0	0
60	0.91	3.49	0.00	5	0	0
61	0.26	0.66	0.00	4	0	0
62	4.41	10.99	1.03	9	−0.211	−0.048
63	1.02	3.50	0.00	5	0	0
64	1.09	3.32	0.00	5	0	0
65	0.96	4.14	0.00	5	0	0
66	1.11	4.07	0.00	5	0	0
67	0.35	0.88	0.00	4	0	0
68	1.17	3.34	0.00	5	0	0
69	3.75	9.32	0.66	9	−0.026	−0.007
70	0.98	3.51	0.00	5	0	0
71	37.80	42.25	35.68	17	−42.680	−1.129
72	22.92	40.52	11.12	17	−13.513	−0.590
73	18.86	27.45	13.93	17	−2.825	−0.150
74	0	0	0	0	0	0
75	0	0	0	0	0	0
76	0.38	1.10	−0.07	14	−1.638	−4.345
77	3.13	0.01	4.54	10	−0.506	−0.162
78	0.37	1.11	0.00	4	0	0
79	0.85	3.10	0.00	5	0	0
80	0.68	2.49	0.00	5	0	0
Total	5.93	8.48	4.70		−63.098	

Note. %N&P refers to the joint reduction percentage of N and P where one unit P is equal to 10 units N. %N and %P refer to the reduction percentages of N and P. CE stands for Cost Effectiveness, which is calculated as the costs divided by the joint reduction percentage of N and P.

Table AI.2. Description of the considered measures at the farm level.

Number	Description
Measure 1	installation of air washers
Measure 2	installation flushing system
Measure 3	coverage of manure storage with tent
Measure 4	spring application and direct under ploughing
Measure 5	acidification of manure
Measure 6	green manure
Measure 7	maximum fertiliser application
Measure 8	all pigs get phase feeding
Measure 9	all pigs get phase feeding plus protein restriction
Measure 10	all pigs get phase feeding plus decreased safety margin
Measure 11	all poultry get phase feeding
Measure 12	all poultry get phase feeding plus protein restriction
Measure 13	all poultry get phase feeding plus decreased safety margin
Measure 14	all bovine animals get limited N plus protein according to the animal need
Measure 15	Measures 1 and 3 taken jointly
Measure 16	Measures 4 and 7 taken jointly
Measure 17	Measures 1, 3, 4, 6, 7 and 14 taken jointly
Measure 18	Measures 1, 3, 4 and 14 taken jointly.

Table AI.3. The estimated parameters for 80 farm sectors.

Sector	h_m	g_m	h_q	g_q	N0	P0	Nmax	Pmax
1	0.445	0	22.7	3.19	10.40	3.36	0.185	0.000
2	3.17	0	305	3.51	1.93	0.57	0.081	0.000
3	3.50	0	311	3.72	1.99	0.56	0.068	0.000
4	0.432	0	60.9	6.18	21.22	3.46	0.107	0.000
5	1.04	0	71.2	5.77	14.27	2.55	0.082	0.000
6	0.000	0	235	5.65	2.77	0.54	0.000	0.000
7	9.98	0	91.6	4.05	4.47	1.13	0.095	0.000
8	5.15	0	30.2	4.41	20.17	4.99	0.091	0.000
9	3.91	0	228	2.98	0.97	0.34	0.187	0.000
10	70.9	0	5092	3.26	0.11	0.03	0.075	0.000
11	57.0	0	5190	3.49	0.11	0.03	0.073	0.000
12	5.05	0	763	5.78	1.59	0.28	0.118	0.000
13	17.8	0	1189	5.39	0.80	0.15	0.087	0.000
14	0.000	0	2.35×10^6	5.45	0.00	0.00	0.000	0.000
15	107	0	3821	3.81	0.10	0.03	0.093	0.000
16	0.425	0	26.0	3.04	7.05	2.34	0.161	0.000
17	0.252	0	4.37	3.20	16.58	5.25	0.185	0.000
18	5.70	0	1815	3.29	1.01	0.31	0.054	0.000
19	2.01	0	33.6	3.09	5.93	2.02	0.176	0.000
20	1.87	0	29.2	3.55	4.57	1.36	0.180	0.000
21	0.422	0	6.02	3.01	13.79	4.65	0.357	0.000
22	0.229	0	10.0	4.22	19.90	4.78	0.331	0.000
23	18.8	0	4137	6.25	0.32	0.05	0.083	0.000
24	1.31	0	71.8	6.51	6.88	1.06	0.099	0.000
25	13.5	0	254	6.73	1.05	0.17	0.079	0.000
26	25.5	0	251	5.70	1.23	0.23	0.086	0.000
27	7.01	0	245	2.82	0.64	0.24	0.218	0.000
28	41.6	1331	1.64×10^4	3.21	0.10	0.03	0.133	0.000
29	0.000	0	2.40×10^4	3.39	0.08	0.02	0.000	0.000
30	6.98	0	405	7.02	1.76	0.25	0.081	0.000
31	2558	0	3.39×10^4	7.01	0.01	0.00	0.047	0.000
32	3.61×10^6	0	1.04×10^6	5.17	0.00	0.00	0.018	0.000
33	1282	0	2.41×10^4	5.66	0.02	0.00	0.052	0.000
34	12.2	0	103	3.22	3.75	1.25	0.047	0.000
35	3.25	0	52.3	2.79	0.66	0.24	0.217	0.000
36	2.94	0	13.9	3.10	1.03	0.33	0.307	0.000
37	1248	0	5.20×10^6	3.42	0.00	0.00	0.157	0.000
38	28.3	0	150	4.10	0.21	0.05	0.149	0.000
39	5.15	0	5.76	3.40	2.08	0.62	0.194	0.000
40	0.248	0	9.67	2.91	19.35	6.90	0.227	0.000
41	1.95	409	3179.0	3.86	1.24	0.33	0.132	0.001
42	0.478	0	29.2	7.08	23.69	3.37	0.091	0.000
43	4.68	0	83.6	6.26	4.69	0.77	0.056	0.000
44	5.55×10^6	0	735	5.54	0.81	0.16	0.001	0.000
45	122	0	19.7	4.85	16.83	3.72	0.026	0.000
46	1.98	0	17.4	3.83	20.72	5.57	0.121	0.000
47	0.463	0	42.3	2.80	5.82	2.13	0.266	0.000
48	72.3	0	2.03×10^5	3.40	0.04	0.01	0.154	0.000
49	1.41	0	91.5	5.65	6.04	1.07	0.111	0.000
50	1.98	0	36.5	3.69	8.87	2.45	0.105	0.000
51	0.594	0	66.1	2.73	4.14	1.57	0.213	0.000
52	0.338	0	17.2	2.59	9.92	3.93	0.220	0.000
53	1.08	0	90.1	3.14	7.65	2.49	0.075	0.000
54	0.972	0	54.3	6.33	10.01	1.59	0.103	0.000
55	1.93	0	35.1	3.51	7.39	2.16	0.117	0.000
56	1.32	0	65.7	5.52	9.12	1.67	0.074	0.000
57	0.150	0	9.18	2.74	29.33	11.19	0.212	0.000
58	9.50	0	6926	3.60	0.41	0.12	0.134	0.000
59	9.16	0	2188	3.30	1.19	0.37	0.066	0.000
60	28.6	0	2601	3.52	1.07	0.32	0.017	0.000
61	0.326	0	28.5	6.38	27.78	4.38	0.106	0.000

Table AI.3. (*continued*)

Sector	h_m	g_m	h_q	g_q	N0	P0	Nmax	Pmax
62	0.000	0	143	5.15	2.85	0.62	0.000	0.000
63	3.52	0	39.1	4.08	9.45	2.40	0.085	0.000
64	18.6	0	55.8	4.92	11.61	2.44	0.042	0.000
65	0.120	0	8.14	3.02	33.94	11.74	0.220	0.000
66	3.88	5493	1626	3.73	0.85	0.24	0.154	0.000
67	0.417	0	41.2	6.43	20.88	3.28	0.110	0.000
68	3.24	0	104	5.39	4.16	0.80	0.087	0.000
69	0.000	0	230	5.55	2.44	0.48	0.000	0.000
70	3.18	0	37.5	3.90	10.12	2.69	0.095	0.000
71	0.000	0	3.77	4.76	55.10	12.88	0.000	0.000
72	0.000	0	192	6.71	18.43	4.10	0.000	0.000
73	0.000	0	497	5.74	7.45	1.54	0.000	0.000
74	0.155	0	14.3	10.57	140.74	13.31	0.166	0.000
75	0.991	0	42.9	10.83	28.74	2.65	0.131	0.000
76	369	156	808	6.15	5.08	0.84	0.118	0.005
77	1.86	4	25.8	4.51	20.28	4.29	0.331	0.350
78	4.91	0	194	5.01	1.37	0.28	0.134	0.000
79	15.1	0	294	3.74	0.78	0.21	0.130	0.000
80	3.84	0	115	3.77	1.84	0.50	0.168	0.000
Total:					761.78	164.87		

Table AI.4. The estimated parameters for WWTPs in 13 different regions.

Region	h_n	h_p	N0i	P0i	Nmaxi	Pmaxi
1	0.500	46.9	22.15	2.00	0.563	0.256
2	13.1	443	1.40	0.19	0.344	0.238
3	1.28	43.3	22.31	2.36	0.220	0.199
4	8.64	292	1.56	0.20	0.469	0.355
5	110	2377	0.36	0.05	0.201	0.164
6	41.9	906	0.75	0.11	0.083	0.066
7	0.198	20.6	60.75	4.69	0.524	0.210
8	0.803	76.3	14.39	1.52	0.546	0.201
9	0.895	34.9	26.36	1.90	0.268	0.304
10	0.288	16.7	34.87	3.67	0.629	0.331
11	1.08	53.1	12.39	1.58	0.485	0.256
12	0.539	11.7	37.57	8.12	0.391	0.215
13	4.42	156	4.34	0.59	0.329	0.218
Total			239.21	26.99		

Table AI.5. The estimated parameters for wetlands.

h_w	c	g_w	AeqN	AeqP	Nmaxw	Pmaxw
4300	63.1	1.335	296	13.3	0.478	0.358

APPENDIX II. RESULTS.

This section presents the emission reductions in percentages for each individual sector for eleven alternative model runs as described in Table 6.

Table AII.1. Percentage of emission reductions by each individual sector for the base case and 10 alternative model runs.

	base case	dry year	wet year	cheap wetlands	expensive wetlands	low retention wetlands	cheap measures	low reduction	50% N load	70% N load	70% N and 75% P load
Nmeas1	11.3	6.4	14.4	0.2	18.5	18.5	18.5	1.0	17.4	18.5	18.5
Nmeas2	8.1	4.8	8.1	0.2	8.1	8.1	8.1	0.8	8.1	8.1	8.1
Nmeas3	6.8	4.2	6.8	0.2	6.8	6.8	6.8	0.7	6.8	6.8	6.8
Nmeas4	5.7	3.2	7.2	0.1	10.7	6.8	10.4	0.5	8.7	10.7	10.7
Nmeas5	3.5	2.0	4.5	0.1	7.3	4.4	6.4	0.3	5.4	8.2	8.2
Nmeas6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas7	1.2	0.7	1.5	0.0	2.5	1.9	2.2	0.1	1.8	5.1	5.1
Nmeas8	0.5	0.3	0.6	0.0	1.0	0.7	0.9	0.0	0.8	2.1	2.1
Nmeas9	12.6	5.1	18.1	0.3	18.7	14.5	18.7	1.1	18.7	18.7	18.7
Nmeas10	6.2	2.5	7.5	0.1	7.5	6.5	7.5	0.6	7.5	7.5	7.5
Nmeas11	7.3	3.0	7.3	0.2	7.3	7.3	7.3	0.7	7.3	7.3	7.3
Nmeas12	5.9	2.4	8.4	0.1	11.8	6.1	10.8	0.5	9.0	11.8	11.8
Nmeas13	3.3	1.3	4.8	0.1	6.9	3.5	6.1	0.3	5.1	8.7	8.7
Nmeas14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas15	4.4	1.8	6.3	0.1	9.1	4.9	8.1	0.4	6.8	9.3	9.3
Nmeas16	10.7	3.4	14.5	0.2	16.1	15.2	16.1	1.0	16.1	16.1	16.1
Nmeas17	7.9	2.5	10.9	0.2	17.4	18.5	14.5	0.7	12.3	18.5	18.5
Nmeas18	5.4	1.7	5.4	0.1	5.4	5.4	5.4	0.5	5.4	5.4	5.4
Nmeas19	2.7	0.9	3.6	0.1	5.6	3.7	4.9	0.2	4.1	11.4	11.4
Nmeas20	3.8	1.2	5.2	0.1	8.1	7.5	7.0	0.3	5.9	16.9	16.9
Nmeas21	5.6	1.8	7.7	0.1	12.1	17.9	10.3	0.5	8.7	25.4	25.4
Nmeas22	7.1	2.3	9.7	0.2	15.1	11.7	13.1	0.6	11.0	31.5	31.5
Nmeas23	8.3	3.1	8.3	0.2	8.3	8.3	8.3	0.8	8.3	8.3	8.3
Nmeas24	6.2	2.1	8.4	0.1	9.9	9.9	9.9	0.5	9.6	9.9	9.9
Nmeas25	4.2	1.4	5.7	0.1	7.9	0.0	7.6	0.3	6.6	7.9	7.9
Nmeas26	1.8	0.6	2.4	0.0	4.0	6.5	3.3	0.2	2.8	8.6	8.6
Nmeas27	9.7	3.4	13.0	0.2	20.3	16.0	17.7	0.9	14.9	21.8	21.8
Nmeas28	10.2	3.6	13.3	0.2	13.3	10.9	13.3	0.9	13.3	13.3	13.3
Nmeas29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas30	3.5	1.2	4.8	0.1	7.5	4.5	6.5	0.3	5.5	8.1	8.1
Nmeas31	1.2	0.4	1.6	0.0	2.5	1.7	2.1	0.1	1.8	4.7	4.7
Nmeas32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas33	1.8	0.6	2.5	0.0	3.9	2.5	3.3	0.2	2.8	5.2	5.2
Nmeas34	0.9	0.3	1.3	0.0	1.9	1.1	1.7	0.1	1.4	3.9	3.9
Nmeas35	16.5	6.5	21.7	0.3	21.7	0.0	21.7	1.4	21.7	21.7	21.7
Nmeas36	14.1	5.2	22.7	0.2	30.7	0.0	25.1	1.1	24.4	30.7	30.7
Nmeas37	10.9	4.4	15.6	0.2	15.7	10.8	15.7	1.0	15.7	15.7	15.7
Nmeas38	6.7	2.5	10.4	0.1	14.9	0.0	12.0	0.5	11.2	14.9	14.9
Nmeas39	4.6	1.6	8.0	0.1	19.4	0.0	8.0	0.3	8.8	0.0	0.0
Nmeas40	5.8	2.8	9.1	0.1	12.0	7.8	10.7	0.5	8.9	22.7	22.7
Nmeas41	11.5	5.5	13.2	0.3	13.2	13.2	13.2	1.1	13.2	13.2	13.2
Nmeas42	2.5	1.2	3.9	0.1	5.2	3.0	4.6	0.2	3.8	9.1	9.1
Nmeas43	1.3	0.6	2.0	0.0	2.7	1.8	2.4	0.1	2.0	5.6	5.6
Nmeas44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Nmeas46	0.7	0.3	1.1	0.0	1.4	0.8	1.2	0.1	1.0	2.8	2.8
Nmeas47	13.5	4.7	22.0	0.3	26.6	17.4	24.8	1.2	20.7	26.6	26.6
Nmeas48	11.7	4.1	15.4	0.3	15.4	11.6	15.4	1.1	15.4	15.4	15.4
Nmeas49	4.3	1.5	7.1	0.1	9.0	5.4	7.9	0.4	6.6	11.1	11.1
Nmeas50	2.1	0.7	3.4	0.0	4.3	2.7	3.8	0.2	3.2	8.8	8.8
Nmeas51	15.1	4.1	21.3	0.3	21.3	19.7	21.3	1.4	21.3	21.3	21.3
Nmeas52	11.1	3.0	17.3	0.2	22.0	17.6	20.4	1.0	17.1	22.0	22.0
Nmeas53	4.5	1.2	6.9	0.1	7.5	4.9	7.5	0.4	6.8	7.5	7.5
Nmeas54	3.9	1.0	6.1	0.1	8.2	5.4	7.1	0.3	6.0	10.3	10.3

Table AII.1. (continued)

	base case	dry year	wet year	cheap wetlands	expensive wetlands	low retention wetlands	cheap measures	low reduction	50% N load	70% N load	70% N and 75% P load
Nmeas55	2.6	0.7	4.1	0.1	5.5	3.9	4.8	0.2	4.0	11.2	11.2
Nmeas56	3.1	0.8	4.9	0.1	6.5	4.0	5.7	0.3	4.8	7.4	7.4
Nmeas57	8.8	2.4	14.2	0.2	18.2	11.4	16.2	0.8	13.5	21.2	21.2
Nmeas58	9.8	2.7	13.4	0.2	13.4	9.9	13.4	0.9	13.4	13.4	13.4
Nmeas59	3.5	1.0	5.7	0.1	6.6	3.6	6.5	0.3	5.4	6.6	6.6
Nmeas60	1.3	0.3	1.7	0.0	1.7	1.3	1.7	0.1	1.7	1.7	1.7
Nmeas61	4.3	1.2	7.0	0.1	9.0	5.2	7.9	0.4	6.7	10.6	10.6
Nmeas62	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas63	1.2	0.3	1.9	0.0	2.4	1.6	2.2	0.1	1.8	5.0	5.0
Nmeas64	0.2	0.0	0.3	0.0	0.4	0.2	0.3	0.0	0.3	0.8	0.8
Nmeas65	7.8	4.2	0.4	0.2	16.0	9.5	14.2	0.7	11.8	22.0	22.0
Nmeas66	9.5	5.2	0.5	0.2	15.4	9.9	15.4	0.9	14.5	15.4	15.4
Nmeas67	3.6	2.0	0.2	0.1	7.5	4.1	6.7	0.3	5.6	11.0	11.0
Nmeas68	2.4	1.3	0.1	0.1	4.9	3.0	4.3	0.2	3.6	8.7	8.7
Nmeas69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas70	1.0	0.5	0.1	0.0	2.0	1.2	1.8	0.1	1.5	4.1	4.1
Nmeas71	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas72	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas74	0.3	0.2	0.4	0.0	0.6	0.4	0.6	0.0	0.5	1.3	1.3
Nmeas75	0.2	0.1	0.3	0.0	0.5	0.4	0.4	0.0	0.4	1.0	1.0
Nmeas76	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nmeas77	0.3	0.6	0.3	0.1	1.4	33.1	0.5	0.5	0.3	0.7	0.8
Nmeas78	7.0	2.8	10.1	0.2	13.4	13.4	12.7	0.6	10.8	13.4	13.4
Nmeas79	3.9	1.6	5.7	0.1	8.4	7.6	7.2	0.4	6.1	13.0	13.0
Nmeas80	6.5	2.6	9.4	0.1	13.9	13.8	12.0	0.6	10.1	16.8	16.8
Pquota1	2.4	2.3	2.9	0.3	6.3	52.6	2.1	1.2	3.2	7.6	7.8
Pquota2	1.2	1.1	1.4	0.1	3.0	23.3	1.0	0.5	1.5	3.9	4.0
Pquota3	1.2	1.1	1.5	0.1	3.1	23.4	1.1	0.5	1.6	4.2	4.3
Pquota4	1.6	1.3	2.0	0.1	3.8	19.8	1.5	0.5	2.3	5.7	5.8
Pquota5	1.8	1.4	2.1	0.1	4.2	22.9	1.6	0.6	2.5	6.3	6.4
Pquota6	2.5	2.0	3.0	0.2	5.9	32.7	2.2	0.8	3.5	9.2	9.3
Pquota7	2.2	1.9	2.7	0.2	5.6	39.1	2.0	0.9	3.0	8.1	8.2
Pquota8	1.7	1.4	2.0	0.1	4.1	27.1	1.5	0.7	2.3	6.1	6.2
Pquota9	1.9	1.0	2.6	0.1	4.1	16.0	1.7	0.5	2.7	6.5	6.5
Pquota10	0.9	0.5	1.3	0.0	2.0	7.2	0.8	0.2	1.3	3.4	3.4
Pquota11	1.0	0.5	1.3	0.0	2.1	7.2	0.9	0.2	1.4	3.6	3.6
Pquota12	1.3	0.6	1.8	0.0	2.8	6.4	1.2	0.2	1.9	4.9	4.9
Pquota13	1.4	0.7	2.0	0.1	3.1	7.4	1.3	0.2	2.1	5.4	5.4
Pquota14	2.1	1.0	2.9	0.1	4.4	10.6	1.9	0.4	3.1	8.1	8.1
Pquota15	1.8	0.9	2.5	0.1	3.9	12.2	1.6	0.4	2.6	6.6	6.7
Pquota16	1.8	1.2	2.2	0.2	4.4	31.9	1.5	0.8	2.4	5.7	5.8
Pquota17	4.9	3.2	6.2	0.4	12.3	84.4	4.4	2.0	6.7	16.1	16.4
Pquota18	0.2	0.1	0.3	0.0	0.5	3.4	0.2	0.1	0.3	0.7	0.7
Pquota19	1.6	1.1	2.0	0.1	4.1	28.6	1.4	0.7	2.2	5.8	5.9
Pquota20	3.1	1.9	4.0	0.3	7.7	49.5	2.8	1.2	4.3	11.4	11.6
Pquota21	3.8	2.5	4.8	0.3	9.7	69.3	3.4	1.6	5.1	13.7	13.9
Pquota22	3.0	1.7	3.9	0.2	7.3	41.4	2.7	1.0	4.2	11.2	11.4
Pquota23	1.6	0.9	2.0	0.1	3.6	18.1	1.4	0.5	2.2	5.6	5.7
Pquota24	4.9	2.7	6.3	0.3	11.1	53.5	4.3	1.4	6.9	17.2	17.4
Pquota25	9.0	4.9	11.6	0.5	20.6	93.4	8.1	2.5	12.8	32.4	32.7
Pquota26	5.6	3.2	7.2	0.4	13.2	69.0	5.0	1.8	7.9	20.9	21.1
Pquota27	2.3	1.5	2.9	0.2	5.7	39.9	2.0	0.9	3.1	7.3	7.5
Pquota28	0.3	0.2	0.3	0.0	0.7	4.3	0.2	0.1	0.4	0.9	0.9
Pquota29	0.3	0.2	0.4	0.0	0.7	4.3	0.3	0.1	0.4	1.1	1.1
Pquota30	3.0	1.5	3.9	0.2	6.8	24.5	2.7	0.7	4.4	11.2	11.3
Pquota31	4.2	2.1	5.5	0.2	9.4	34.1	3.8	1.0	6.1	16.1	16.2
Pquota32	0.6	0.3	0.8	0.0	1.4	6.4	0.5	0.2	0.9	2.3	2.3
Pquota33	3.1	1.6	4.0	0.2	7.1	30.1	2.8	0.8	4.4	11.6	11.7
Pquota34	1.2	0.7	1.5	0.1	2.9	18.3	1.0	0.4	1.6	4.3	4.3

Table AII.1. (continued)

	base case	dry year	wet year	cheap wetlands	expensive wetlands	low retention wetlands	cheap measures	low reduction	50% N load	70% N load	70% N and 75% P load
Pquota35	8.1	5.9	10.6	0.7	19.2	98.4	6.8	3.4	10.6	24.6	25.1
Pquota36	23.9	16.8	32.2	2.0	54.6	98.8	21.3	9.4	32.8	66.6	67.9
Pquota37	0.0	0.0	0.0	0.0	0.1	0.5	0.0	0.0	0.0	0.1	0.1
Pquota38	18.4	11.7	25.1	1.3	42.8	98.8	16.6	6.0	25.9	61.2	62.0
Pquota39	33.8	23.1	45.9	2.6	78.8	98.9	30.3	12.5	46.9	98.9	98.9
Pquota40	1.4	1.1	2.0	0.1	3.5	27.0	1.2	0.6	1.8	4.8	4.9
Pquota41	0.1	0.1	0.2	0.0	0.3	1.7	0.1	0.0	0.1	0.4	0.4
Pquota42	2.1	1.3	3.1	0.1	4.8	19.4	1.9	0.5	3.0	7.9	8.0
Pquota43	2.8	1.9	4.2	0.2	6.6	29.3	2.6	0.8	4.1	10.8	10.9
Pquota44	1.4	1.0	2.1	0.1	3.3	16.3	1.3	0.4	2.0	5.4	5.4
Pquota45	2.0	1.4	2.9	0.1	4.7	25.3	1.8	0.6	2.8	7.4	7.5
Pquota46	1.2	0.9	1.8	0.1	3.0	18.8	1.1	0.5	1.7	4.4	4.5
Pquota47	1.3	0.9	1.9	0.1	3.2	24.4	1.1	0.6	1.7	3.9	4.0
Pquota48	0.1	0.0	0.1	0.0	0.1	0.9	0.0	0.0	0.1	0.2	0.2
Pquota49	2.2	1.2	3.4	0.1	5.1	23.4	2.0	0.6	3.1	8.0	8.1
Pquota50	1.6	1.0	2.5	0.1	4.0	24.9	1.5	0.6	2.3	6.0	6.1
Pquota51	1.1	0.8	1.6	0.1	2.9	24.9	0.9	0.6	1.4	3.4	3.5
Pquota52	1.6	1.2	2.3	0.2	4.4	38.0	1.4	0.9	2.1	5.0	5.2
Pquota53	0.6	0.4	0.8	0.1	1.5	11.5	0.5	0.3	0.8	2.0	2.0
Pquota54	2.9	1.4	4.3	0.2	6.7	31.4	2.6	0.8	4.1	10.5	10.6
Pquota55	1.9	1.2	2.7	0.2	4.8	34.3	1.7	0.8	2.6	6.9	7.0
Pquota56	2.0	1.0	2.9	0.1	4.7	24.4	1.8	0.6	2.8	7.2	7.3
Pquota57	1.2	0.8	1.7	0.1	3.0	23.5	1.0	0.5	1.6	3.8	3.9
Pquota58	0.2	0.1	0.3	0.0	0.4	3.0	0.2	0.1	0.3	0.6	0.6
Pquota59	0.2	0.1	0.3	0.0	0.4	3.0	0.2	0.1	0.2	0.6	0.6
Pquota60	0.2	0.1	0.3	0.0	0.5	3.0	0.2	0.1	0.3	0.7	0.7
Pquota61	2.1	0.9	3.2	0.1	4.8	20.4	1.9	0.5	3.0	7.6	7.6
Pquota62	2.4	1.2	3.7	0.2	5.7	28.4	2.2	0.7	3.4	9.1	9.2
Pquota63	1.8	1.0	2.8	0.1	4.4	26.3	1.6	0.6	2.5	6.8	6.9
Pquota64	1.5	0.8	2.3	0.1	3.5	18.3	1.3	0.5	2.1	5.6	5.7
Pquota65	1.1	1.0	0.1	0.1	2.8	19.9	1.0	0.5	1.5	3.7	3.8
Pquota66	0.3	0.3	0.0	0.0	0.8	5.0	0.3	0.1	0.5	1.1	1.1
Pquota67	1.6	1.1	0.1	0.1	3.6	14.8	1.4	0.4	2.3	5.8	5.9
Pquota68	2.2	1.6	0.2	0.1	5.0	23.7	2.0	0.6	3.1	8.1	8.2
Pquota69	1.7	1.2	0.1	0.1	3.9	17.8	1.5	0.5	2.4	6.3	6.4
Pquota70	1.3	1.1	0.1	0.1	3.2	19.1	1.2	0.5	1.8	4.9	4.9
Pquota71	1.2	2.1	1.2	0.3	4.8	80.2	0.9	1.7	1.0	2.7	3.1
Pquota72	0.1	0.1	0.1	0.0	0.3	5.0	0.1	0.1	0.1	0.2	0.3
Pquota73	0.1	0.1	0.1	0.0	0.3	5.1	0.1	0.1	0.1	0.2	0.2
Pquota74	0.5	0.6	0.6	0.1	1.6	20.7	0.4	0.4	0.6	1.5	1.6
Pquota75	0.9	1.1	1.0	0.2	2.8	34.6	0.7	0.7	1.0	2.6	2.8
Pquota76	0.1	0.2	0.1	0.0	0.4	5.8	0.1	0.1	0.1	0.3	0.3
Pquota77	0.5	0.9	0.5	0.1	2.1	45.3	0.4	0.7	0.4	1.1	1.3
Pquota78	4.5	2.9	6.2	0.3	10.7	58.7	4.1	1.5	6.4	15.6	15.8
Pquota79	3.0	2.1	4.0	0.2	7.4	49.4	2.6	1.2	4.1	10.4	10.6
Pquota80	3.2	2.3	4.4	0.3	8.1	53.8	2.9	1.3	4.5	11.0	11.2
STPN1	13.6	12.2	11.0	0.3	27.4	13.3	24.9	1.2	20.6	54.8	54.7
STPN2	6.4	6.1	5.5	0.1	12.9	6.3	11.7	0.6	9.7	25.8	25.8
STPN3	4.6	3.8	4.1	0.1	9.3	4.5	8.5	0.4	7.0	18.6	18.6
STPN4	10.4	8.4	9.1	0.2	21.0	10.2	19.1	0.9	15.8	41.9	41.9
STPN5	2.9	2.8	2.5	0.1	5.9	2.9	5.4	0.3	4.5	11.9	11.8
STPN6	3.4	3.3	2.9	0.1	6.9	3.4	6.3	0.3	5.2	8.3	8.3
STPN7	10.2	11.1	8.5	0.2	20.7	10.0	18.8	0.9	15.6	41.3	41.3
STPN8	11.9	11.8	10.1	0.3	24.1	11.7	21.9	1.1	18.2	48.3	48.2
STPN9	5.4	5.3	4.6	0.1	10.8	5.3	9.9	0.5	8.2	21.7	21.6
STPN10	13.2	12.1	11.5	0.3	26.7	13.0	24.3	1.2	20.1	53.5	53.4
STPN11	9.1	8.9	4.2	0.2	18.4	8.9	16.8	0.8	13.9	36.9	36.8
STPN12	1.3	1.5	1.0	0.0	2.5	1.2	2.3	0.1	1.9	5.1	5.1
STPN13	7.3	7.0	6.2	0.2	14.7	7.1	13.3	0.7	11.0	29.3	29.3

Table AII.1. (*continued*)

	base case	dry year	wet year	cheap wetlands	expensive wetlands	low retention wetlands	cheap measures	low reduction	50% N load	70% N load	70% N and 75% P load
STPP1	20.0	25.6	16.8	13.0	25.6	25.6	25.6	12.8	0.0	0.0	14.0
STPP2	5.2	6.8	6.4	3.4	23.8	23.8	6.9	11.9	0.0	0.0	3.6
STPP3	16.3	18.3	16.2	10.6	19.9	19.9	19.9	10.0	0.0	0.0	11.5
STPP4	30.6	35.5	28.8	19.9	35.5	35.5	35.5	17.8	0.0	0.0	21.5
STPP5	8.6	11.4	10.6	5.6	16.4	16.4	11.5	8.2	0.0	0.0	6.1
STPP6	6.6	6.6	6.6	5.3	6.6	6.6	6.6	3.3	0.0	0.0	5.8
STPP7	14.3	18.7	17.1	9.3	21.1	21.1	19.0	10.5	0.0	0.0	10.1
STPP8	13.5	13.1	14.2	8.8	20.1	20.1	18.0	10.1	0.0	0.0	9.5
STPP9	24.8	17.8	24.9	16.1	30.4	30.4	30.4	15.2	0.0	0.0	17.4
STPP10	26.3	21.8	26.9	17.1	33.1	33.1	33.1	16.6	0.0	0.0	18.5
STPP11	18.5	25.6	2.9	12.0	25.6	25.6	24.5	12.8	0.0	0.0	13.0
STPP12	2.9	3.9	3.9	1.9	20.2	21.5	3.9	9.4	0.0	0.0	2.0
STPP13	19.8	21.8	17.8	12.9	21.8	21.8	21.8	10.9	0.0	0.0	13.9
n	24.2	24.5	24.0	29.8	18.3	15.9	20.1	29.3	24.8	47.8	47.8
Total cost	286.8	291.4	282.3	38.2	949.9	1784.8	217.9	338.8	290.0	1456.1	1484.9
P reduction (%)		30.0	30.0	30.0	30.0	30.0	30.0	30.0	24.6	38.7	42.8
N reduction (%)		30.0	30.0	30.0	30.0	30.0	30.0	30.0	33.1	59.8	59.8

Note. Nmeas is the percentage of emission reduction through measures at farms (see Table 3 for the corresponding regions and farm types of the 80 farm sectors). Pquota is the percentage of quota restrictions on farms. STPN (and STPP) is the percentage of N (and P) reduction at WWTPs though measures per region. *n* is the fraction of N retention by wetlands.