

**Optimal control of dynamic point and non-point pollution in a coastal ecosystem:
agricultural abatement versus investment in waste water treatment plants**

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Abstract

We apply optimal control modeling to examine in a dynamic framework how public resources should be allocated to small-scale water protection efforts in agriculture or alternatively to investments in large-scale waste water treatment plants to control point source loads. The building of waste water treatment plants is characterized by high set-up costs as compared to the operating costs. We focus on the following questions: Under what conditions should investment in a wastewater treatment plant be undertaken and what determines the optimal time to invest? What should be the rate of wastewater purification in case that investment is undertaken? What should be the rate of reduction in nutrient load from agriculture? We show how the environmental damage from nutrient concentration affects the optimal timing of investment in waste water treatment capacity. We determine the optimal timing of investment, the rate of nutrient load reduction from point versus non-point sources, and the optimal switching policies from control of non-point pollution only to control of both non-point and point sources.

Key words: nonpoint-source pollution, point-source pollution, timing of investment

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1 Introduction

Nutrient flows from land-based sources pose a threat to freshwater and marine ecosystems. The most heavily loaded marine areas in Europe show symptoms of severe eutrophication resulting from nutrient enrichment (see for example Ærteberg et al., 2001). Toxic algae outbreaks are a common phenomenon during the warm summer months and filamentous algae cover the seabed in coastal areas. Increased algae production reduces oxygen concentration in the deep water, which in the worst case results in total oxygen depletion. Eutrophication degrades water ecosystems, bottom fauna, fish stocks and drinking water quality. It has a negative impact on human well-being both directly and through the lost value of fisheries and recreational activities.

The state of marine and fresh water ecosystems can be improved by reducing nutrient loading. However, the choice of measures is not straightforward. The costs of different policy measures in reducing nutrient loads vary substantially due to both economic and biophysical factors. Inland sources of polluting nutrients include agriculture, traffic, municipalities and industry. Many environmental assessments identify agriculture as the major cause of surface quality problems in developed countries. (Shortle & Abler, 2001). For example in the Nordic countries, municipal and industrial pollution loads have been significantly reduced over the last few decades, but the agricultural sector continues to pose problems due to intense farming technologies (Turner et al., 1999). Regulation of agricultural pollution is a challenging task. The emission processes are complex, the pollution sources are diffuse, enforcement costly and the policy context involves conflicting objectives, such as environmental protection and agricultural income support.¹ Realistically, instead of water quality policies have to be based on factors that only indirectly affect pollution but that are relatively easily observed (see e.g. Griffin and Bromley, 1982; Shortle and Dunn, 1986; Horan and Ribaud, 1999). For a survey, see Russell and Shogren (1993) or Romstad et al. (1997).

¹ The European Commission has recently made a proposal to reform the Common Agricultural Policy (COM (2003) 23 final). It is claimed that the major objective of the reform is to give farmers a long-term perspective for sustainable agriculture. In particular, the implementation of the Commission reform would remove environmentally negative incentives and provide further encouragement for more sustainable farming practices.

Despite the relative ease of controlling pollution from point sources, poor processing of urban and industrial waste waters continues to contribute to nutrient loading in many regions. For example in the Gulf of Finland, one of the most eutrophied sub-basins of the Baltic Sea, urban wastewaters from the densely populated St. Petersburg region reach the sea through the River Neva drainage basin. In the Finnish coastal waters of the Gulf of Finland, the largest anthropogenic phosphorus source is agriculture. The development of the nutrient load and eutrophication in the Gulf of Finland largely depends on the combined effect of environmental policy in Russia and in Finland. Reduction of nutrient loading requires considering control of both point and non-point sources. Typical questions raised in designing policies to reduce nutrient loading in coastal zones receiving both point and non-point loads are: How to find a balance between regulation of agricultural non-point sources and industrial or municipal point sources? and What is the suitable level for action, e.g. watershed, regional, national or international?

Previous dynamic analyses on eutrophication of coastal waters have focused on agricultural non-point loading alone. Hart and Brady (2002) and Hart (2003) have considered the impacts of alternative policy goals and time-lags of abatement due to upstream and downstream measures. Nævdal (2002) has also used a dynamic framework to examine optimal regulatory policies when thresholds effects are present so that the eutrophication process is characterized by discrete jumps in the state variable. Existing studies analyzing the reduction of both point and non-point source loads have applied a static framework to study the trade-offs between abatement in point and non-point sources assuming that the abatement technology is already in place (e.g., Elofsson 2003, Malik et al. 1993). In reality setting up facilities to remove nutrients from point sources involves an irreversible investment, whereas agricultural abatement occurs through reversible small scale measures such as changes in fertilizer use and other farming practices.

This paper applies optimal control modeling to explicitly analyze the investment required to establish waste water treatment plants to reduce nutrient loads from point sources. We examine in a dynamic framework how public funding should be allocated to investments in large-scale waste water treatment plants to control of point source loads or alternatively to small-scale water protection efforts in agricultural non-point sources. When point source control requires costly investments, the choice of optimal abatement and investment policies becomes a two-stage optimal control problem. We build on the results developed in

Tomiyama (1985) and Amit (1986) and study the following questions: Under what conditions should investment in a waste water treatment plant be undertaken and what determines the optimal time? What should be the rate of cleaning wastewater in case that investment is undertaken? What should be the rate of reduction in nutrient load from agriculture before and after establishing waste water treatment capacity?

2 The model

Consider a coastal zone subject nutrient loading from agriculture and from municipal wastewater. We focus on the solution of an environmental agency attempting to minimize the environmental damages from nutrient accumulation through reducing nutrient loading. Reducing leaching from agriculture does not involve set-up costs, whereas cleaning wastewater is only possible if an investment is undertaken to construct waste water treatment capacity (WWTC). There are thus two potential phases of nutrient load reduction. Prior to establishing WWTC, only nutrient loads from agricultural sources can be controlled. If the capital outlay is incurred to establish waste water treatment capacity, nutrient loads from both agricultural and municipal sources can be reduced.

We use a two-phase optimization model building on that of Amit (1986) to characterize the interactions between nutrient accumulation, investment and nutrient reduction rates. *We first consider the social planner's solution.* Let us first introduce the notation. The nutrient flows consist of leaching from agriculture, $N(t)$, and municipal waste water, $S(t)$. Agricultural leaching can be reduced through decreasing the amount of fertilizer applied, changes in tillage practices, and use of buffer strips. Reducing agricultural leaching entails a cost in terms of reduced profits. Let $\gamma(t)$ denote the rate of nutrient abatement in agriculture and $c_\gamma(\gamma N)$ the associated cost, with $c_\gamma'(\gamma N) > 0$ and $c_\gamma''(\gamma N) \geq 0$. The regulator chooses the rate of reduction in agricultural leaching to balance the costs and benefits of abatement. Since only positive rates of abatement are possible and at most a 100 % reduction of nutrient leaching can be achieved, $\gamma(t)$ must satisfy

$$0 \leq \gamma(t) \leq 1$$

The amount of municipal waste water $S(t)$ is largely determined by population size. By assumption, population size and hence $S(t)$ are fixed. The amount of nutrients from waste water washed into the receiving body of water can be reduced through organically or chemically cleaning waste water. However, if municipal wastewater is to be cleaned, there is a necessary outlay on the establishment of waste water treatment capacity at the initiation point of those operations. For simplicity, we assume that the required investment, K , is fixed. The size of this investment does not depend on the rate of cleaning waste water. Further, it has no impact on the unit cost of cleaning waste water. These assumptions are probably an oversimplification. Nevertheless, they illustrate the principle of having to incur a capital outlay to enable reducing nutrient loads from a point source.

Once waste water treatment capacity is in place, the cost of cleaning waste water at the rate $\beta(t)$ is $c_\beta(\beta S)$, with $c_\beta'(\beta S) > 0$ and $c_\beta''(\beta S) \geq 0$. Since only positive rates of cleaning are possible and at most 100 % of nutrients can be removed, $\beta(t)$ must satisfy

$$(1) \quad 0 \leq \beta(t) \leq 1.$$

The stock of nutrients, $P(t)$, increases as nutrient leachates from agriculture or waste water enter the ecosystem. A proportion α is attenuated through natural decay. The accumulation of nutrients then follows

$$(2) \quad \dot{P} = \begin{cases} [1 - \gamma(t)]N(t) + S(t) - \alpha P(t) & 0 \leq t \leq t_1 \\ [1 - \gamma(t)]N(t) + [1 - \beta(t)]S(t) - \alpha P(t) & t_1 \leq t \leq t_2 \end{cases}.$$

Finally, damages in the coastal ecosystem are a function of the nutrient stock, $D(P)$, with $D'(P) > 0$ and $D''(P) \geq 0$.

Having outlined the basic relationships, we now state the two-phase nutrient reduction model. Consider an environmental agency that is concerned about a coastal ecosystem with economic, ecological and technological characteristics outlined previously. The environmental agency seeks to minimize the sum of damages from nutrient accumulation and the costs of reducing agricultural nutrient loading and cleaning waste water, or equivalently to

maximize the negative of the sum over damages and costs. The environmental agency wishes to determine optimally the rate of reducing agricultural nutrient loading, $\gamma(t)$, switching time t_1 from agricultural abatement only to waste water treatment and agricultural abatement, and finally the rate of waste water treatment $\beta(t)$. By assumption, the environmental agency's discount rate remains unchanged.

Formally stated, the environmental agency's objective is to choose $\gamma(t)$, $\beta(t)$ and t_1 optimally so as to maximize

$$(3) \quad \int_0^{t_1} e^{-rt} \{-D[P(t)] - c_\gamma[\gamma(t)N]\} dt + \int_{t_1}^{t_2} e^{-rt} \{-D[P(t)] - c_\gamma[\gamma(t)N] - c_\beta[\beta(t)S]\} dt - \Delta K e^{-rt_1}$$

The objective in (3) is maximized subject to

$$(4) \quad \dot{P} = \begin{cases} (1 - \gamma(t))N + S - \alpha P(t) & 0 \leq t \leq t_1 \\ (1 - \gamma(t))N + (1 - \beta(t))S - \alpha P(t) & t_1 \leq t \leq t_2 \end{cases}$$

$$(5) \quad 0 \leq \gamma(t) \leq 1, \quad 0 \leq \beta(t) \leq 1$$

$$(6) \quad t_0, P_0 \text{ fixed, } t_1, P(t_1) \text{ free, } t_2 \text{ fixed, } P(t_2) \text{ free; } P(t) \text{ nonnegative for all } t.$$

The indicator function Δ takes up value 1 if the investment is undertaken and 0 otherwise:

$$(7) \quad \Delta = \begin{cases} 1 & t_1 < t_2 \\ 0 & t_1 = t_2 \end{cases}.$$

The first integral in the objective function represents the damages and abatement costs when nutrient leachates can be reduced only in agriculture, while the second represents the damages and abatement costs when a waste water treatment plant is in place, enabling removal of nutrients from waste water in addition to control of agricultural leaching.

3 The optimal policies

Problem (3)-(7) may be viewed as one of optimal control with two potential phases. We will employ the results outlined in Amit (1985) to analyze the problem. Let $\tau(t)$ denote the current value multiplier associated with (4). The multiplier $\tau(t)$ reflects the social shadow cost of accumulated nutrients. The current value Hamiltonian for the problem is (assuming $\lambda_0 = 1$)

$$(8) \quad H = \begin{cases} H_1 & 0 \leq t \leq t_1 \\ H_2 & t_1 \leq t \leq t_2 \end{cases}$$

where

$$(9a) \quad H_1 = -D(P(t)) - c_\gamma(\gamma(t)N) + \tau\{(1 - \gamma(t))N + S - \alpha P(t)\}$$

$$(9b) \quad H_2 = -D(P(t)) - c_\gamma(\gamma(t)N) - c_\beta(\beta(t)S) + \tau\{(1 - \gamma(t))N + (1 - \beta(t))S - \alpha P\}.$$

Let μ_1, μ_2, μ_3 and μ_4 be Lagrange multipliers, and let L denote the Lagrangian (the augmented Hamiltonian). Then

$$(10a) \quad L_1 = -D(P(t)) - c_\gamma(\gamma(t)N) + \tau\{(1 - \gamma(t))N + S - \alpha P\} \\ + \mu_1[1 - \gamma(t)] + \mu_2\gamma(t)$$

$$(10b) \quad L_2 = -D(P(t)) - c_\gamma(\gamma(t)N) - c_\beta(\beta(t)S) + \tau\{(1 - \gamma(t))N + (1 - \beta(t))S - \alpha P\} \\ + \mu_1[1 - \gamma(t)] + \mu_2\gamma(t) + \mu_3[1 - \beta(t)] + \mu_4\beta(t)$$

with

$$(11a) \quad \mu_1 \geq 0, \mu_1[1 - \gamma(t)] = 0,$$

$$\mu_2 \geq 0, \mu_2\gamma(t) = 0,$$

$$(11b) \quad \mu_3 \geq 0, \mu_3[1 - \beta(t)] = 0,$$

$$\mu_4 \geq 0, \mu_4 \beta(t) = 0,$$

so μ_1 and μ_2 , and similarly μ_3 and μ_4 , cannot be simultaneously positive.

The necessary conditions for the social planner's problem are

$$(12) \quad \frac{\partial L_i}{\partial \gamma} = \frac{\partial H_i}{\partial \gamma} - \mu_1 + \mu_2 = -c_\gamma'(\gamma(t)N)N - \tau N - \mu_1 + \mu_2 = 0 \quad i = 1,2$$

so that if $\mu_1 = 0$ and $\mu_2 > 0$, then

$$(13a) \quad \frac{\partial H_i}{\partial \gamma} < 0 \quad \text{and thus } \gamma(t) = 0;$$

if $\mu_1 > 0$ and $\mu_2 = 0$, then

$$(13b) \quad \frac{\partial H_i}{\partial \gamma} > 0 \quad \text{and thus } \gamma(t) = 1;$$

if $\mu_1 = 0$ and $\mu_2 = 0$, then

$$(13c) \quad \frac{\partial H_i}{\partial \gamma} = 0 \quad \text{and } 0 \leq \gamma(t) \leq 1;$$

$$(14) \quad \frac{\partial L_2}{\partial \beta} = \frac{\partial H_2}{\partial \beta} - \mu_3 + \mu_4 = -\tau S - c_\beta'(\beta S)S - \mu_3 + \mu_4 = 0$$

so that if $\mu_3 = 0$ and $\mu_4 > 0$, then

$$(14a) \quad \frac{\partial H_2}{\partial \beta} < 0 \quad \text{and thus } \beta(t) = 0;$$

if $\mu_3 > 0$ and $\mu_4 = 0$, then

$$(14b) \quad \frac{\partial H_2}{\partial \beta} > 0 \quad \text{and thus } \beta(t) = 1;$$

if $\mu_3 = 0$ and $\mu_4 = 0$, then

$$(14c) \quad \frac{\partial H_2}{\partial \beta} = 0 \quad \text{and } 0 \leq \beta(t) \leq 1;$$

$$(15) \quad \tau'(t) = r\tau(t) - \frac{\partial H_i}{\partial P} = (r + \alpha)\tau(t) + D'(P(t));$$

$$(16) \quad \tau(t_2) = 0;$$

$$(17) \quad -H_2(t_1)e^{-rt_1} + rK\Delta e^{-rt_1} + H_1(t_1)e^{-rt_1} = 0 \quad \text{if } 0 < t_1 < t_2;$$

$$(17a) \quad -H_2(0) + rK\Delta + H_1(0) \leq 0 \quad \text{if } 0 = t_1 < t_2;$$

$$(17b) \quad -H_2(t_1)e^{-rt_1} + rK\Delta e^{-rt_1} + H_1(t_1)e^{-rt_1} \geq 0 \quad \text{if } 0 < t_1 = t_2;$$

$$(18) \quad \lim_{t \rightarrow t_1^-} \tau(t_1) + \underbrace{\frac{\partial K e^{-rt}}{\partial P}}_{=0} = \lim_{t \rightarrow t_1^+} \tau(t_1).$$

The necessary conditions characterize the optimal solution. We next turn to observing and discussing the optimal policies.

3.1 Optimal abatement of agricultural leaching

From (13a)-(13c) we have that the optimal rate of reduction in agricultural leaching is defined by

$$(19a) \quad 0 \leq \gamma \leq 1 \text{ and } c_\gamma'(\gamma(t)N) = -\tau(t) \quad \text{or}$$

$$(19b) \quad \gamma = 1 \text{ and } c_\gamma'(\gamma(t)N) < -\tau(t) \quad \text{or}$$

$$(19c) \quad \gamma = 0 \text{ and } c_\gamma'(\gamma(t)) > -\tau(t).$$

We get the familiar result that nutrient loading should be abated at the level where the marginal cost of doing so just equals the society's shadow cost of pollution (see e.g. Xepapadeas 1992). The proportion of nutrients abated obviously cannot exceed 1. If the unit cost of preventing any agricultural leaching from reaching the ecosystem is smaller than the shadow cost of pollution, the optimal rate of abatement in agriculture is set at its upper limit. If the unit cost of agricultural abatement exceeds the shadow cost of pollution for any nonnegative value of $\gamma(t)$, no abatement of agricultural leaching is undertaken.

3.2 *Optimal rate of cleaning wastewater from point source*

Assuming that a waste water treatment plant is built, i.e., $0 \leq t_1 < t_2$, we next establish the optimal rate of cleaning waste water. From (14) we have that

$$(20a) \quad 0 \leq \beta(t) \leq 1 \text{ and } c_\beta'(\beta(t)S) = -\tau(t) \quad \text{or}$$

$$(20b) \quad \beta(t) = 1 \text{ and } c_\beta'(\beta(t)S) < -\tau(t)$$

$$(20c) \quad \beta(t) = 0 \text{ and } c_\beta'(\beta(t)S) > -\tau(t).$$

The waste water treatment plant will be built only if $\beta(t_1) > 0$, otherwise (17) cannot hold. This implies that a necessary condition for the capacity investment to be undertaken is that $c_\beta'(\beta(t_1)S) \leq -\tau(t_1)$. Again, waste water is optimally treated at a rate where the marginal cost of cleaning equals the shadow cost of pollution. If the shadow cost of pollution exceeds the marginal cost of waste water treatment, water is cleaned at maximum capacity. If the

marginal cost of treating waste water exceeds the shadow cost of pollution for all $0 < \beta(t) \leq 1$ and $0 \leq t_1 \leq t_2$, no investment in waste water treatment capacity is undertaken.

Consider the case where $c_\gamma'(\varepsilon) < c_\beta'(\varepsilon)$ for $\varepsilon \rightarrow 0^+$. As the social shadow cost of pollution $\tau(t)$ rises in absolute value, pollution concentration is first controlled through increased efforts to reduce leaching from agriculture, with the policy commencing at $c_\gamma'(\varepsilon) = -\tau(t)$ for $\varepsilon \rightarrow 0^+$. Cleaning waste water becomes desirable once the shadow cost of pollution in absolute value rises to a level where $c_\beta'(\varepsilon) = -\tau(t)$ for $\varepsilon \rightarrow 0^+$. The optimal timing of installing a waste water treatment plant will also depend on the cost of the initial investment. We will address the optimal timing of the investment below.

We may also obtain an expression for the social shadow cost of nutrient concentration $\tau(t)$. Integrating (15) and using the transversality condition (16) yields

$$(21) \quad \tau(t) = - \int_t^{t_2} e^{-(\alpha+r)(s-t)} D'(P(s)) ds$$

Equation (21) defines the value of the multiplier $\tau(t)$ associated with the level of nutrient concentration $P(t)$ at each point, given that the optimal policy is followed throughout. Note that since $D'(P(t)) > 0$, $\tau(t)$ is negative.

4 Building a waste water treatment plant

We now investigate the questions of whether and when to begin treating wastewater. The analysis is divided into three cases.

Case 1. When cleaning municipal wastewater is relatively cheap compared to reducing leaching from agriculture, so that the former is no more expensive than the latter once a waste water treatment plant is in place, it seems desirable to install the waste water treatment plant in the beginning of the planning horizon. Formally, by combining (17a) and (9) we have that

$$(22) \quad -\tau(0)\beta(0)S - c_{\beta}(\beta(0)S) - rK \geq 0$$

must hold for $t_1 = 0$ to be optimal. Condition (22) means that the shadow value of nutrient concentration avoided through commencing waste water treatment immediately is at least as large as the sum of the interest payments on capital invested in constructing a waste water treatment plant and the cost of cleaning waste water at the rate $\beta(0)$.

Case 2. When reducing leaching from agriculture is relatively cheap compared to cleaning wastewater, it seems desirable not to invest in a waste water treatment plant and instead concentrate efforts on controlling agricultural nutrient loading. Formally, for $0 < t_1 = t_2$ to be optimal, condition (17b) must hold. Combining (17b) and (9) with $\Delta = 0$ yields

$$(23) \quad c_{\beta}(\beta(t_1)S) \geq -\tau(t_1)\beta(t_1)S .$$

If for all $0 \leq t_1 \leq t_2$ the cost of cleaning waste water at the rate $\beta(t_1)$ exceeds the shadow cost of nutrient concentration that could be avoided through the cleaning effort, reduction of nutrient load should take place only in agriculture and no waste water treatment plant should be built.

If condition (23) does not hold and a point in time is reached at which the cost of constructing a waste water treatment plant and commencing cleaning of municipal wastewater just equals the shadow value of thereby avoided accumulation of nutrients, it seems optimal to invest in the treatment capacity. In view of (17), this condition is satisfied for $0 < t_1 < t_2$, i.e. when a waste water treatment plant is constructed after a period reducing agricultural leaching only. Note also that the marginal shadow cost of pollution τ must be equal for either abatement alternative, as indicated by (18). Combining (17) and (9) yields

$$(24) \quad -\tau(t_1)\beta(t_1)S - c_{\beta}(\beta(t_1)S) - rK = 0 .$$

We now examine the impact of changes in the parameters upon t_1 in case (24) is satisfied, i.e., a phase of agricultural abatement only is followed by a phase of waste water treatment

and agricultural abatement. Consider the case of constant marginal cost of waste water treatment. It is possible to show that an increase in the (exogenously determined) amount of waste water advances the commencement of waste water treatment, i.e.

$$(25) \quad \frac{\partial t_1}{\partial S} < 0.$$

It is also possible to show that

$$(26) \quad \frac{\partial t_1}{\partial K} > 0.$$

Thus, as could be expected, an increase in the capital outlay K required for building a waste water treatment plant causes a prolonged period of only agricultural abatement. This result is due to the higher interest payment that has to be met.

We may now summarize the solution to problem (3)-(7) as follows: If conditions (20a) or (20b) together with (22) hold at the initial nutrient concentration level, the optimal policy begins waste water treatment immediately. As stated earlier, building a waste water treatment plant immediately is optimal if treating wastewater is relatively cheap compared to reducing leaching from agriculture. If instead the cost of cleaning waste water exceeds the shadow cost of the associated increase in nutrient concentration throughout the planning period, no investment in waste water treatment plants is undertaken (equation 23). Finally, if condition (24) holds for a point in time $0 < t_1 < t_2$, then the optimal policy commences with agricultural abatement and switches to a regime of waste water treatment and agricultural abatement when the reward from the additional abatement just equals the reward from agricultural abatement only plus interest payments on capital invested in waste water treatment capacity.

5 Conclusion

We have examined optimal abatement of nutrient loading in an eutrophicated coastal zone where two sources contribute to the nutrient load: agricultural leaching and municipal waste water. A program to reduce the nutrient loads comprises two potential phases. Initially, small scale measures can be adopted to reduce agricultural loading. If investment is undertaken to

establish waste water treatment capacity, nutrient loads from municipal waste water can also be controlled. We have formulated an investment and abatement model that incorporates both abatement technologies, and investigated a two-phase dynamic optimization problem. The major findings relate to the rate of abatement in agriculture and in waste water treatment, and the optimal switching policies from agricultural abatement only to a regime where both abatement alternatives are used.

We outlined the conditions under which each of the following three abatement policies should be undertaken. First, in case treating waste water is relatively cheap, waste water treatment plants should be built immediately. Second, if treating waste water is relatively expensive, only agricultural abatement should take place. We also observed that an exogenous increase in the amount of municipal waste water advances the adoption of waste water treatment. Third, if neither of these cases holds and a point in time is reached where the cost savings from using both abatement alternatives just equal the cost savings from agricultural abatement only plus the interest payments on the investment, a period of only agricultural abatement is followed by abatement through waste water treatment and reduction of agricultural loading.

An interesting extension to this study would be to explicitly consider the uncertainties inherent to the management nutrient loads. The two abatement measures differ not only in scale effects but also in the degree and source of uncertainty. In agriculture, the uncertainties pertain most notably to precipitation influencing the nutrient loss and adoption of the measures by the farmers in the catchments, whereas the uncertainties of large scale abatement investments are related to financing of the investments and the time it takes from planning to construction and operation of new treatment facility.

References

- Ærteberg G. et al. (2001). Eutrophication in Europe's coastal waters. European Environment Agency. Topic report no. 7. 115 p.
- Amit, R. (1986). Petroleum reservoir exploitation: switching from primary to secondary recovery. *Operations Research* 34: 534-539.
- Elofsson, K. (2003). Cost-effective reductions of stochastic agricultural loads to the Baltic Sea. *Ecological Economics* 47: 13-31.
- Griffin, R.C. and Bromley, D.W. (1982). Agricultural runoff as a non-point externality: theoretical development. *American Journal of Agricultural Economics* 64: 547-552.
- Hart, R. (2003). Dynamic pollution control – time lags and optimal restoration of marine ecosystems. *Ecological Economics* 47: 79-93.
- Hart, R. and M. Brady (2002). Nitrogen in the Baltic Sea – policy implications of stock effects. *Journal of environmental management* 66: 91-103.
- Horan, R.D. and Ribaud, M.O. (1999). Policy objectives and economic incentives in for controlling agricultural sources of pollution. *Journal of the American Water Resources Association* 35: 1023-1035.
- Malik A.S., D. Letson & S.R. Crutchfield (1993). Point/nonpoint source trading of pollution abatement: choosing the right trading ratio. *American Journal of Agricultural Economics* 75:959–967.
- Nævdal, E. (2002). Optimal regulation of eutrophying lakes, fjords, and rivers in the presence of threshold effects. *American Journal of Agricultural Economics* 83:972-984.
- Romstad, E., Simonsen, J.W., Vatn, A. (Eds.), (1997). Controlling Mineral Emissions in European Agriculture: Economics, Policies and the Environment. CAB International, Oxon, UK.
- Russell, C.S. and Shogren, J.F. (1993). Theory, Modeling and Experience in the Management of Nonpoint-Source Pollution. Kluwer Academic Publishing, Boston, MA.
- Shortle, J.S. and Abler, D.G. (1999). Agriculture and the environment. In J. van den Bergh (ed.) *Handbook of Environmental and Resource Economics*. Edward Elgar, Cheltenham. p. 159-176.
- Shortle, J.S. and Dunn, J.W. (1986). The relative efficiency of agricultural source water pollution control policies. *American Journal of Agricultural Economics* 68: 668-677.

- Tomiyama, K. (1985). Two-stage optimal control problems and optimality conditions. *Journal of economic dynamics and control* 9:317-337.
- Turner, R.K. & Georgiou, S. & Gren, I. & Wulff, F. & Barrett, S. & Söderqvist, T. & Bateman, I.J. & Folke, C. & Langaas, S. & Zylicz, T. & Mäler, K-G. & Markowska, A. (1999). Managing nutrient fluxes and pollution in the Baltic: an interdisciplinary simulation study. *Ecological Economics* 30: 333-352.
- Xepapadeas, A. P: (1992). Environmental policy design and dynamic nonpoint-source pollution. *Journal of environmental economics and management* 23: 22-39.