Management of Eutrophicated Coastal Zones

The quest for an optimal policy under spatial heterogeneity

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To Joann, Jonas, and Marcus

Abstract

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To manage coastal zones suffering from eutrophication in the presence of spatial heterogeneity requires an understanding regarding the complexity of such problem. This thesis contributes to the understanding about setting an optimal policy design for sources whose effect on the recipient varies spatially. The first three articles considers the nitrogen load to the Stockholm archipelago caused by emission sources within its river basin, while the fourth consider the nitrogen load to the Baltic Sea originating from a smaller part of this coastal zone, Himmerfjärden, and its catchment area.

Article I shows that efficiency in coastal zone management is only possible if abatement costs are connected to the damage on the recipient. Articles II and III estimates efficiency losses of uniform policy instruments in the presence of spatial heterogeneity with respect to sources. While article II compares the cost between a cost-effective policy and a uniform percentage reduction by one type of abatement measure, article III compares three types of uniform policy with a cost-effective using four different types of abatement measures. Article II and III indicates significant efficiency losses of uniform policies. Article IV introduces the uncertainty aspect of the management problem described in article I, and how it affects cost as well as the cost-effective allocation of abatement measures. The thesis indicates potential gains of using a spatially differentiated policy instrument in reducing the effects of eutrophication in the Stockholm Archipelago, and highlights the complexity of coastal zone management in general.

Keywords: cost-effectiveness, efficiency, spatial heterogeneity, policy instruments, eutrophication, nitrogen abatement, coastal zone management, stochastic pollutant transport.

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Preface

Being accepted to the society-planning program at Stockholm University, I soon discovered that a whole semester was designated to the dreadful study of economics. There was no way out, I just had to endure it. However, on an early stage, against all of my prejudice against this subject, I came to enjoy the classes and discovered its potential. The head teacher of this semester, Margareta Johannesson, played a major role in this process, so did my fellow student Peter Skogman-Thoursie. Being interested in environmental issues I started thinking of applying the economic toolbox to that area. After obtaining my Bachelor degree, majoring in economics, I spent two years in Florida, the first year working and the second year studying at the graduate program in economics at the University of South Florida (USF). During this time my wishes to work within the field of environmental economics strengthened. The first year after coming back to Sweden, I took classes in economics and natural sciences. However, by a coincidence I spotted an opening as a research assistant at the Beijer Institute, a position that was given to me by Tore Söderqvist, despite the fact that I'm not a "djurgårdare". Shortly after, with the encouragement from Tore and Ing-Marie, I started my path towards a Ph.D. in economics, a journey whose destination I arrive at with the completion of this thesis.

I'm very thankful for the support, feedback, guidance, and patience given to me by my supervisor Ing-Marie Gren. I would also like to thank my discussant at the licentiate seminar, Eirik Romstad, for giving me valuable comments on my Licentiate thesis. I'm very grateful to the discussants at my licentiate seminar, and final seminar at SLU, Rob Hart and Yves Surry for giving me valuable comments. I would like to thank John Swinton, whom I met at my time at USF. He has been giving me valuable comments, on the economics as well as the grammar, on the thesis. I also want to thank my wife's uncle Rick Rees for helping me out with the grammar.

I would like to mention several people at SLU that have been helpful during this time regarding the thesis or in other aspects, Christina Brundin, Monica Campos, Dennis Collentine, Katarina Elofsson, Clas Eriksson, Peter Frykblom, Knut-Per Hasund, Fredrik Holstein, and Ficre Zehai.

I'm grateful to my "family" at Beijer for providing that special kind of atmosphere, rarely found elsewhere. All you (Beijer tjejer), treating me like a little brother, *i.e.* either helping me or teasing me: Sara Anyiar, Jessica Andersson, Anne-Sophie Crépin, Miriam Huitric, Åsa Jansson, Christina Leijonhufvud, Sandra Lerda, Anna Sjöström, Åsa Soutukorva, and Ingela Ternström. I also want to mention Johan Colding and Max Troell, and their special kind of humour. A special thanks to Karl-Göran Mäler, always having time to support a Ph.D. student stuck on some trivial problem, and Tore Söderqvist for his valuable comments on the articles and support throughout these years.

The importance of friends and family cannot be underestimated in this process, as everyone who has reached this point knows. I would especially, like to thank

my parents for always believing in me and supporting the choices I have made in my life. Thanks also to my sisters, and their families, my cousins, my extended family, and all my in-laws around the world. I especially want to send a thought to my grandmother, Greta “Hulda” Andersson, who past away this summer. A special thanks to all my friends for just being there, no one mentioned no one forgotten, you know who you are.

Last, but by now means least, I would like to thank the three most important people in my life. My wonderful wife and companion in life, Joann, to whom I owe so much, and our two wonderful boys, Jonas and Marcus, who have enriched my life to an extent that I thought was not possible.

Financial support has been provided by MISTRA (trough the MARE programme), and I’m very grateful for their generosity.

Articles appended to the thesis

Article I-IV

This thesis is based on the following articles, which will be referred to by their Roman Numerals:

I. Scharin, H. The efficient management of coastal zones in theory and practice: an application of nitrogen reduction to the Stockholm Archipelago. (Manuscript.)

II. Scharin, H. Comparing two approaches of estimating costs of uniform and spatially differentiated policy instruments. (Manuscript.)

III. Scharin, H. Efficiency losses of uniform policy instruments in the presence of spatial heterogeneity of marginal abatement cost. (Manuscript.)

IV. Scharin, H., Gren, I-M., and Destouni G. 2000. Cost effective management of stochastic water pollution. In: Environmental Modeling and Assessment 5: 193-203, Kluwer Academic Publishers.

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Contents

Introduction

The pollution of certain coastal zones caused by nutrients, such as nitrogen and phosphorus, is an increasing problem in certain parts of the world. An increased population density of the river basins related to these coastal zones together with the following industrial, residential, and agricultural pollution has generated a situation in which the environmental services provided of coastal zones decreases or loses its value over time (see *e.g.* Cederwall & Elmgren, 1990; Rabalais *et al.*, 1996; Turner *et al.*, 1999; Wulff, 2000; Boesch, 2001; Mitsch *et al.*, 2001; Morgan & Owens, 2001). Managing coastal zones with regard to land-based pollution loads often demands the need to understand the spatial aspects of such environmental degradation. To obtain a certain environmental quality in the coastal zones at minimum cost requires an understanding regarding how the location of pollution sources affects such quality.

The objective of this thesis is to analyze and describe the procedure of reaching an efficient and/or cost-effective management of coastal zones, in a case where spatial heterogeneity of nitrogen emission sources plays a significant role for the optimal way to reach any given target. An efficient load is characterized by the fact that no further changes in load can be made without causing reductions in the society’s net-gains, while cost-effectiveness implies that any reduction target is obtained at minimum cost to the society. When the damage to a coastal zone differs for sources, due to their location, good data availability is important. The implications of spatial heterogeneity in the quest for a cost-effective policy are also analyzed. The empirical application in the first three articles is made for the same recipient and its drainage basin, the coastal zone of the Stockholm Archipelago. The fourth article is applied to Himmerfjärden and its drainage basins, a smaller part of the Stockholm Archipelago river basin. This thesis links the benefits with costs of pollution abatement, taking into consideration the interdependency between different abatement measures. The concept used could easily be transferred to the management of other recipients characterized by similar problems.

The purpose of this introduction is to place the four articles into a context, deliver a review of the work that has been done regarding cost-effective management of ambient targets, and finally explain the scope and contributions of the four articles. This introduction is organized as follows; first, the problem of eutrophication and its characteristics is provided. Thereafter, the economics of coastal zone management under spatial heterogeneity is explained, and a literature review related to the subject is provided. The main findings and contributions of the four articles are finally presented, together with suggestions for further research regarding these problems.

Description of the eutrophication in the Stockholm Archipelago

The Stockholm Archipelago together with its river basin is the area studied in the first three articles, while Himmerfjärden and its catchment is studied in the fourth, in which the marine water of the Baltic Sea is the recipient of concern. The river basin for the Stockholm Archipelago is the geographical area from which the major part of the nitrogen load to this recipient originates. This river basin covers an area of about 26,500 km2 of which Lake Mälaren accounts for a little more than four percent. Forest dominate the land, covering 51 percent of the area, while arable land accounts for 17 and pasture for two percent. Himmerfjärden, the area studied in article IV, is located in the southern part of the Stockholm Archipelago and covers an area of 1286 km2. This area is separated into four coastal water basins, defined by the sea bottom thresholds, and their respective drainage basin. The study areas are chosen due to the availability of data regarding emission sources, their respective impact on the recipient (Johansson, 1989: Statistics Sweden, 1995; Johnsson & Hoffman, 1997; Elmgren & Larsson, 1997; Engqvist, 1997; Arheimer & Brandt, 1998; Persson *et al.*, 1989; Willén, 2001; Färlin, 2002) and estimates of the damage caused by the eutrophication in the Archipelago (Söderqvist & Scharin, 2000; Sandström *et al.*, 2000; Soutukorva, 2001).

Nutrients, i.e. nitrogen and phosphorus, from rural as well as urban sources within the drainage basin, cause an eutrophication of the coastal zone. The process of eutrophication, i.e. an increase of carbon supply to the water mass, is generated by an increase in the load of nutrients to the recipient stimulating the growth of plants (Nixon, 1985). The Baltic Sea and its coastal zones are suffering from the effects of eutrophication, caused by the increased inflow of nutrients. This has generated higher primary production in the photic zone of the sea, causing decreased water transparency, increased algae blooms, increased frequency and severity of oxygen deficiency in bottom waters, as well as reduction of the bottom fauna (Cederwall & Elmgren, 1990). Phosphorus is excluded from the discussion, since nitrogen is the limiting nutrient of coastal areas of this part of the Baltic (Granéli *et al.,* 1990). The limiting nutrient is the one currently determining the level of primary production. No reductions of the primary production will, therefore, occur by reducing the non-limiting nutrient, i.e. phosphorus, to the Archipelago.

Economics of coastal zone management

In this chapter, the economic characteristics of the pollution in a coastal zone are described. Economics, as a science, provides a toolbox able to determine the necessary conditions for reaching an environmental target at least cost. Apart from explaining the problem from an economic perspective, the steps linking costs of abatement with the benefits of the same is described. How to reach a cost-effective allocation of abatement using different policy instruments is also discussed. Finally, a review of the literature on recipient management under spatial heterogeneity of sources is provided.

Market imperfections

Nitrogen emission from sources is, in economic terms, regarded as a negative externality. This means that the producer of this pollutant is not forced to consider the effect the environmental damage, caused by this pollutant, has on the utility of a third person. For example, a farmer located in the river basin is not forced to consider how downstream reduction in water transparency affects an individual when determining how much fertilizer to apply on his land. This is reflected in that the producers cost of producing one more unit (marginal cost) of the good is less then the society's marginal cost of this production, since the latter includes the cost of damage. If the product's market price is determined by the producer's marginal cost it will send the wrong signal to the buyers, generating an overproduction of this good or service, thereby implying that the nitrogen load to the Archipelago is larger than what would be the case if the society's costs were included into the decision function of the polluter and thereby the market price.

The damage of the nitrogen load is taking place in the Stockholm Archipelago. The Stockholm Archipelago is a unique area from a natural point of view, exhibiting great recreational and esthetical values to people. This coastal zone can be regarded as a common pool resource with open access, since no person can be restricted from enjoying the Archipelago's recreational value, a value not necessarily decreasing by the consumption of a third person. This non-excludability and non-rivalry of the consumption of water quality in the Archipelago is in economic terms referred to as a public good. Therefore, the load of nitrogen, caused by various activities, reaching the Stockholm Archipelago is described as a negative externality on a public good. Under these circumstances an efficient load cannot be obtained without government intervention internalizing the cost of damage caused by nitrogen emissions into the polluter's decision rule.

Efficiency, cost-effectiveness and policy instruments under spatial heterogeneity

If the marginal cost of damage caused by the nitrogen load, exceeds the marginal cost of reducing this damage, reductions must be made in order to obtain efficiency (Pareto-optimality). An efficient load is found at a point where the marginal damage of eutrophication is equal to the marginal abatement cost of reducing this load. That is, where the cost of reducing the load by one unit equals the benefits of such reduction. Pareto-optimality is achieved if the implemented policy internalizes the cost of eutrophication into the polluter's production decision in a way guaranteeing that each source is confronted with the damage cost generated by its emissions. Connecting costs of abatement with actual benefits triggered by abatement is necessary in order to determine the Pareto-optimal nitrogen load. The efficient load is induced if sources are subject to a charge equal to the marginal damage they cause to the recipient.

However, Pareto-optimality in the use of resources is not necessarily always the objective of decision makers. Reduction targets might be determined by other facts, especially if the information required to determine the Pareto-optimal level is not available. In an attempt to balance the negative consequences of eutrophication, *e.g.* anoxic deep waters, with the positive effects of increased nutrient availability, i.e. higher fish catches, Rosenberg *et al.* (1990) suggests that management of the Baltic Sea should strive for a load of nutrients representative of the mid-1950's. This may be one of the reasons behind the, seemingly arbitrarily selected, goal of a 50 percent reduction of nutrient inputs to the Baltic Sea (Helcom, 1993). Even under such a non Pareto-optimal target, it is desirable to obtain cost-effectiveness in the allocation of abatement measures. Cost-effectiveness requires that abatement measures be allocated so that no further reductions of the load can be made without increasing the cost.

In order to achieve the targeted nitrogen load to the Archipelago, some kind of policy has to be implemented forcing the sources of this pollutant to internalize the additional cost of eutrophication. Since the marginal abatement cost to the recipient differs between sources, a policy considering the spatial differences between sources is necessary in order to achieve a cost-effective allocation of abatement measures. The use of a uniform policy instrument such as uniform tax, uniform required percentage reduction, or uniform quantity of reduction, would under these circumstances not reach the targeted reduction at the least cost (transaction costs excluded), since it is based on the assumption that the damage generated by a unit of emissions is the same for all sources. There are several options in the setting of a policy aimed at reducing the pollutants from specific sources. Whether it is optimal to chose market based instruments, such as taxes/subsidies and tradable emission/ambient permits, or command-and-control instruments, depends to a large degree on the shapes of the marginal cost and marginal damage curves, the presences of uncertainties concerning these curves and whether there are any thresholds with regard to the damage (see *e.g.* Weitzman, 1974; Kolstad, 1987; Gren, 2004). Furthermore, the choice of policy influences the distribution of abatement cost. This might have implications on the political feasibility of policies as well as the enforcement costs of policies, the former being discussed in article III.

Whether to direct the policy towards emissions or the receptor is the issue of several discussions in the literature review below. An ambient based tax would only go into effect when the targeted load to receptor is exceeded, while a, so-called, effluent charge implies that the polluters pay a tax for emissions at source. A choice also has to be made whether policies should be uniform or differentiated over sources. In the presence of spatial heterogeneity regarding the marginal abatement cost to the recipient only the latter guarantees cost-effectiveness. However, due to distributional concerns and/or difficulties in monitoring compliance the former might be chosen.

Since there exists no market for a good water quality in the Archipelago, a hypothetical one has to be constructed in order to obtain some kind of estimate of the damage costs to society generated by this pollution. This can be obtained by finding out how much people are willing to pay (WTP) for an improvement in the water quality of the Archipelago. Water transparency is used as an indication of the environmental quality in the Stockholm Archipelago in the study from which the value of a reduced eutrophication is obtained (Söderqvist & Scharin, 2000).

Since water transparency in the Archipelago can be regarded as a public good, people's marginal willingness to pay has to be summarized horizontally in order to obtain the value of any improvement. Two different survey techniques have been applied to obtain this WTP; a contingent valuation (CV) survey (Söderqvist &

Scharin, 2000) and a travel cost method (Sandström *et.al.,* 2000; Soutukorva, 2001). For a description of these methods see for example: Bockstael *et al.,* (1987), Bishop & Heberlein (1990), and Freeman (2003). The value obtained by a contingent valuation survey can be questioned on the basis of the hypothetical way of estimating values and are also subject to a lot of criticism, (see Phillips & Zeckhauser, 1989; Diamond & Hausmann, 1994; Carson *et al.,* 2001). Similar studies have been done regarding the benefits of the water quality of Chesapeake Bay, another coastal zone suffering from eutrophication; see *e.g.* Morgan & Owens (2001), Krupnick (1988), Bockstael *et.al.* (1989) and Lipton (2004).

In order to estimate the environmental damage generated by a specific source, one must comprehend the environmental chain, which ties this specific pollutant source with damage on the recipient. It is vital to complement economic information with information made available by natural scientists, in order to link socio-economic costs and benefits of managing the water quality of coastal zones. Several studies concerning eutrophication have addressed the importance of integrating natural and social sciences as well as including spatial concerns when dealing with this problem (see *e.g.* Sharp & Bromley, 1979; Shortle & Dunn, 1986; Rabalais *et al.,* 1996; Gren *et al.,* 2002; Boesch, 2001; Mitsch *et al.,* 2001; Wulff *et al.,* 2001; Elofsson, 2003).

The transport of pollutants from a specific source to the recipient gives rise to problems of environmental allocation in space. Transfer functions need to be established that relate an emissions source at one point in space to an ambient level of concentration at another point. In this thesis the transformation of nitrogen on its trajectory from source to recipient, which differs between sources, is established in order to connect emissions with damage. The proportion of the emission reaching a receptor differs due to differences in the buffering capabilities of the trajectory paths connecting emissions with load to recipient, a common characteristics for pollutants transported by water. The links between source and recipient can be summarized in three basic steps: production of emissions, transport of pollutants from source to recipient, and damage generated at recipient due to the concentration of the pollutant.

The first link implies identification of the sources causing this damage on the water quality of the recipient. The major part of the nitrogen load to the Archipelago originates from sources within its river basin. In this river basin the main sources of nitrogen are wastewater treatment plants, leakage from farmed land caused by the deposition of fertilizers, atmospheric deposition, industrial discharge into water, and leakage from forests. This thesis focuses on the first two of these sources due to data constraints. The sources are separated with regard to whether they discharge directly into a water body or if they originate from land. This distinction is motivated by the fact that land originated sources are subject to the buffering capabilities of land as well as Lake Mälaren, while direct discharges only are subject to the buffering capabilities of the latter, if not located adjacent to the recipient. Sources are further separated with regard to in which of the river basin’s 33 drainage basins they are located. The same discussion applies to Himmerfjärden, by replacing the lake basins of Lake Mälaren with the coastal basins of Himmerfjärden and the Archipelago with the marine water of the Baltic Sea.

The next link is to determine the proportion of indirect nitrogen discharges caused by fertilizer deposition that reaches the water body of either lake Mälaren or the Archipelago. Plants utilize some part of the deposited nitrogen, while a fraction leaks away from the root zone. Leaching of nitrogen from fertilization is a function of crop management, water run-off, soil type and meteorological conditions (Johnsson & Hoffman, 1997). Leaching nitrogen from land deposition can thereafter reach a recipient by water transportation, during which it is subject to plant assimilation, sedimentation and denitrification, reducing the amount of nitrogen. The fraction of nitrogen that does not reach a water body, is referred to as retention. Geohydrology, soil-type, land cover, topography, and climate are some of the factors determining retention. Leaching and retention therefore determine the load to either Lake Mälaren or the Archipelago from land deposited nitrogen. The region studied is characterized by great variations in retention (Arheimer & Brandt, 1998). Uncertainty regarding this retention of the pollutants has implications on the cost of reaching a probabilistic pollutant load target.

As mentioned, direct discharges into a waterbody are not subject to land retention. The nitrogen load into either Mälaren or the Archipelago of adjacent drainage basins is the sum of the proportion of indirect discharges that reaches the water body in question and the direct discharges into this waterbody. Lake Mälaren is located in the center of the river basin and can be divided into five lake basins. The nutrient sink capacity of these different basins is of great significance in determining the different impacts on the Archipelago of depositions originated from adjacent drainage basins (Persson *et al.,* 1989). This capacity is a function of factors such as spatial variation in temperature, water residence time, variation of hydrography, lake area and volume, and inorganic nitrogen concentrations (Arheimer & Brandt, 1998). Nitrogen is transported within Lake Mälaren eastwards towards the Archipelago. The nitrogen load to any lake basin is, therefore, subject to its own buffering capacity as well as the buffering capacity of any downstream lake basin.

The nitrogen load to Stockholm Archipelago originates from adjacent drainage basins and the inflow of nitrogen by Norrström, which connects this recipient with Lake Mälaren and its drainage basins. After the linkage between emission of nitrogen sources and their load to the Archipelago is established, the effect this load has on the nitrogen concentration needs to be determined. This nitrogen load effects the concentration of the same in the Archipelago, which in turn causes the eutrophication (Wulff *et al.,* 2001). This concentration can be linked to one of the effects of eutrophication, namely the decrease in water transparency. Färlin (2002) determined the relationship between nitrogen concentration and Secchi-depth in the Archipelago during the summer months.

There are several abatement measures available to reduce the nitrogen load to the Archipelago. The costs of these measures have to be determined. Due to the transformation of nitrogen on its path to the recipient, these cost estimates have to be divided by the fraction of nitrogen reaching the recipient in order to obtain an estimate regarding each measure’s cost of reducing the load to the recipient.

Having linked sources with damage, and costs of abatement with the benefits it generates, it is possible to determine the optimal nitrogen load to the Archipelago and the cost-effective allocation of abatement measures of reaching such load as well as any other targeted load.

In conclusion, managing a water recipient from a drainage basin perspective in a cost-effective way requires information regarding data over emission sources, abatement measures, as well as models describing the relationship between emissions and damage on a recipient. Spatial heterogeneity of sources affects the costs of abatement as well as the most suitable policy instrument for realizing the objective target in a cost-effective way.

Literature review regarding optimal policy under spatial heterogeneity

There is an abundance of literature concerning the management of a recipient under spatially heterogeneous conditions. The hardship lies in designing a policy instrument generating the cost-effective allocation of abatement between the different pollutant sources, in the presence of spatial heterogeneity. The objective of the following literature review is to give an overview of how theoretical and empirical studies have evolved in order to determine the optimal management of the environment in the presence of spatial heterogeneity in marginal abatement cost to a recipient.

The major part of the discussion in the articles has been regarding whether an effluent charge is the least-cost policy to reach an ambient quality target (of either air or water) or not. Along with the theoretical framework of the different policies many case studies have been made as well. During the seventies discussions evolved around the quest for a least-cost strategy to reach a certain ambient air or water quality target. The articles consisted of theoretical and empirical studies in which the spatial heterogeneity of pollution sources played a significant part. First, the articles highlighting the spatial aspect with regard to the source recipient approach are presented. Thereafter, articles regarding the quest for the best policy to achieve an ambient target are reviewed. Articles criticizing the use of effluent charges, and market based polices in general, in reaching ambient targets are then described, followed by articles suggesting policies directed at the ambient environmental state. A review is thereafter made regarding articles comparing and trying to explain the underlying cause regarding the magnitude of cost differences between the alternative policies. Finally, the debate in the American Economic Review whether policies should be determined on a national or local level is summarized.

Ambient quality targets vs. effluent charges

This section will give a summary of the pioneer articles concerning cost-effective policies for an ambient target under spatial heterogeneity, especially focusing on the discussion regarding effluent charges.

Kneese (1964, p. 108) introduces the term effluent charges in his seminal book The Economics of Regional Water Quality Management. Effluent charges would be set so to induce upstream abatement activity as long as the cost of such abatement is less than the marginal downstream damage costs, thereby implying efficiency in abatement. An effluent charge would reach the ambient quality target at lower social cost than policies requiring uniform treatment or uniform reduction in effluent discharges by each discharger. However, whether it represents the least cost strategy is debated in several of the articles reviewed. A first step to estimate the damage caused by pollution of waterways is taken by Kneese & Bower (1968). They are also the first to empirically examine the differences in costs between uniform and spatially differentiated policies.

The initial framework model for reflecting the physical links between emissions of pollutants with the damage they cause, as described in the previous section, is developed by Russell (1971), and Russell & Spofford (1972). Rather than meeting ambient air and water quality standards, the authors maximize the social welfare subject to constraints on levels of production, and consumption as well as requirements for transports, treatment, and discharge of residuals. The initial step of their model is to include a production function relating inputs with outputs. Thereafter, an environmental diffusion model connecting the discharge point with the locations of one or several receptor is presented. Finally, a receptor damage function describing the presence of the pollutant in the receptor with the resulting damages is established. Their model illustrates the connection between costs and benefits of any ambient reduction target.

Baumol & Oates (1971) emphasize the hardship of determining the optimal effluent charge for an ambient target as well as the benefits these generate in an empirical setting. According to the authors the optimal Pigouvian tax cannot be determined a priori for the new damage level since damage functions are likely to change with the state of the environment. The authors suggest a system of standards and prices, ‘the environmental pricing and standards procedure’, that are more flexible and determined by the ambient water or air quality target. The optimal uniform effluent charge is found by an iterative procedure directed by the difference between actual and targeted emissions, whereby an initial rough estimate of such charge is used and then varied over time until the desired ambient pollution standard is achieved. The authors admit that the ‘method will, in general, not result in an optimal allocation of resources, but the procedure will at least represent the least-cost method of realizing the specific standards’ (p.51). One of this policy’s advantages, according to the authors, is that it is not dependent on huge amount of information. Baumol (1972) suggest that the analysis is applicable for air pollution as well.

Tietenberg (1973a; 1973b), on the other hand, claims that such a uniform effluent charge cannot represent the least-cost solution in the presence of spatial heterogeneity regarding the effect emissions have on the concentration of pollutants at a specific receptor. His solution to the problem is a modification of the Baumol-Oates’s model (1971). By applying the Baumol-Oates’s model for each zone under a spatially differentiated policy over several zones instead of only one, cost-effectiveness of reaching an ambient quality target is achieved.

However, the author points out that the administrative information requirements of a differentiated policy are larger than for a uniform, and also that the political feasibility of such a policy might be uncertain due to its distributional effects. Tietenberg states that ‘the optimal number of zones is that number such that for any larger number of zones the marginal transaction costs of administrating one more zone would exceed the marginal gain in resource cost reduction and for any smaller number of zones the marginal gains in resource cost reduction of an increase in zones would exceed the marginal transaction costs of administrating the policy for a larger set of zones’ (1973a, p.202). Exactly where this point lies is an empirical question and cannot be determined a priori according to Tietenberg. Another argument against the use of a uniform effluent charge is that it provides no incentives to the emitters to relocate their production to areas where the damage caused by their emissions is less.

Abrams & Barr (1974) show how an estimated set of differentiated charges on the application of fertilizer nitrogen can be applied into the environmental pricing and standards system (EPS) of Baumol & Oates. The authors use a spatial linear programming model to link the agricultural use of nitrogen fertilizers with the nitrate concentration of Illinois surface waters. They estimate how differentiated taxes affect the net income of farmers differently depending on their location, as well as how it affects the agricultural market and thereby agricultural production in adjacent regions.

Horner (1975) supports the Baumol-Oates proposition that effluent charges can achieve a specified level of water quality at lowest possible cost (under the questionable assumption that transaction costs do not differ with different policies). He presents a concise review of the case for effluent charges. The area studied is the two hydrological basins of the San Joaquin valley in California. However, he only compares the cost of effluent charges with no control and with the cost of removing nitrate-nitrogen (NO3–N) by a treatment plant, excluding a comparison with a cost-effective policy.

Hamlen (1977) provides additional support to the Baumol-Oates’ claim that an effluent charge represents the least-cost policy to reach an ambient target. His extension of their model proves that, even though the allocation of resources is not optimal under an effluent charge, it represents the quasi-optimal Pareto solution (i.e. second-best) for a competitive economy in the sense that consumers will have maximized their utility for the given pollution level. The author develops a theoretical approach for estimating the proper effluent tax using available econometric or input-output models for the region of interest. However, these estimates require more information than the problem considered by Baumol and Oates (1972), but would, on the other hand, require fewer iterations in the search of an optimal effluent charge.

Tietenberg (1978a) questions the result of Hamlen (1977), based on the limitation of the author’s model. His argument is based on the questionable assumption of Hamlen’s model that the pollutant transfer coefficient does not differ between emitters. That is, the proportion of emissions that reaches a recipient does not vary between sources. Literature of natural science concerning pollutants transformation in nature (see Kneese, 1971b) reveals that this is rarely the case, but rather, the fraction reaching the recipient varies from emitter to emitter.

‘To explore a number of economic, administrative and legal issues, which impinge on the design of a system of effluent charges to achieve the national ambient air quality standards at minimum costs’ is the objective of the next article by Tietenberg (1978b, p.265). He seeks out to find out the nature of an effluent charge fulfilling the conditions of cost-effectiveness. Should such a charge be uniform or spatially differentiated and should it be implemented nationally or locally are the questions the author is interested in. Tietenberg points out that a ‘spatially differentiated policy can be implemented for several different degrees, and a uniform charge represents merely the extreme case of zero spatial differentiation’ (p.266). How to determine the degree of spatial differentiation of emission charges is discussed at length in this article, and he argues that it should be regarded as a policy variable. The author also discusses the administrative practicality of a spatially differentiated charge as opposed to a uniform policy. He comes to the conclusions that not only are spatially differentiated charges cost-effective but also realistic, since the only additional information required in moving from a uniform towards a differentiated emission fee is the transfer coefficient linking the emissions from sources with the load to a recipient.

Tietenberg extends his analysis to the marketable emission permits in reaching an ambient air standard (Tietenberg, 1980), in which a dynamic dimension regarding the emission patterns is added to the model. The policy of an ambient differentiated permit is in this article compared, in terms of costs as well as administrative feasibility, to an emission discharge permit. The author notes that administrative costs of an ambient differentiated control scheme implies the desirability and even optimality of a zoned system lying intermediate between the two extremes of spatial uniformity and full spatial differentiation. Tietenberg comes to the conclusion that an ambient differentiated permit has potential to achieve air quality goals at a minimum cost, if certain administrative obstacles could be dealt with.

Bohm & Russell (1985) suggest that in the general case of multiple ambient standards, and lack of information on total control cost, an iterative procedure may eventually lead to achievement of the ambient standards. However, their main conclusion is that there is no guarantee that this is the cost-effective way of meeting the standards. The authors’ show how the case made by Kneese (1964) has to be modified as inconvenient elements of reality is explicitly recognized and dealt with.

In a paper by Ermoliev, Klassen, & Netjes (1996), the pricing approach of environmental pollution originally proposed by Baumol and Oates is extended to the case of multiple receptors. The authors prove that environmental agencies can develop a charge adjustment procedure, such as suggested by Baumol and Oates, that achieves ambient standards at multiple receptors at minimum costs, and fairly quickly. The regulator’s difficulty to obtain full information concerning the pollution control cost for every single emission source, which is necessary in order to reach an ambient target in a cost-effective way, is emphasized in this paper. As opposed to the conclusion by Bohm & Russell (1985), the authors prove that it is possible to determine a vector of ambient charges and resulting emission charges to attain standards at minimum costs. However, due to its complexity and the time of converging, such a system might not be considered practical according to the authors. Their conclusion is that it makes no real difference for the feasibility of emission charges whether environmental targets are formulated in terms of emission goals or a set of ambient concentration standards, even if the central agency has no information on the control costs of sources.

In a theoretical paper, Zylicz (2003) models cost-effective pollution reduction in a drainage basin, and compares the ability of market based policy instruments (taxes and tradable permits) to reach a target reduction level at one or several recipients. In his model Zylicz assumes linear functional relationships regarding discharges and their effect on the recipient. That both taxes and tradable permits can be used to achieve cost-effective abatement is proven by economic theory. Zylicz points out that the information requirements differ between the two instruments, in that the marginal abatement cost must be known to the policy maker in order to determine the taxes generating the target load reduction, which is not the case for tradable permits. The author states that in the presence of significant fixed costs of abatement measures market based instruments alone cannot generate a cost-effective solution.

Criticism against effluent charges

A number of articles have criticized the use of a market based policy instrument, such as an effluent charge. This criticism has been based on the hardship of implementing market based policies, as well as the complexity that is often the case when dealing with ambient targets in the presence of asymmetric information.

An article questioning the feasibility of effluent charges, and market based policies in general, is presented by Rose-Ackerman (1973). She emphasizes the hardship of establishing and enforcing compliance of an effluent charge, whether it is uniform or spatially differentiated, and argues that any real world application of such a policy would be likely to fail due to its complexity. The author argues for the use of command-and-control instrument.

That effluent charges would be more cost-effective than uniform reduction standards, as claimed by Horner (1975), is questioned by Jacobs & Casler (1979). They compare both the social cost and the cost to farmers of achieving given levels of reduction in phosphorus discharge from crop reduction. Costs are estimated for effluent taxes as well as uniform reduction in the Falls Creek watershed of New York State. In their case the total cost of an effluent charge adding the reduction of income of the farmer is 2.7 to 13.3 times higher than the cost of a uniform reduction policy. As Tietenberg (1973a; 1973b), they also point out that the resulting inequity in redistribution of income caused by an effluent charge might be hard for society to accept.

Helfand & House’s (1995) objective is to make an empirical evaluation of policies to reduce the pollution of non-point-sources (NPS) under heterogeneous conditions. Their article focuses on policy instruments on inputs, which are motivated due to the hardships of implementing differentiated policies. The study considers empirical costs associated with uniform input taxes and regulations regarding the lettuce production in California on two different types of soil. Results indicate that regulations imply higher profits for farmers compared to taxes. Helfand and House emphasize the difficulties of getting compliance under a differentiated tax on fertilizers since this input can be resold on the market. The authors come to the conclusion that a uniform input regulation is not necessarily that inefficient if chosen carefully. However, the authors points out, that as areas under study become more heterogeneous it is likely that the social cost of uniform instruments increase.

Ambient target based policies

As opposed to policies directly aimed at emissions several alternative policies have been proposed towards developing cost-effective policies aimed, at the concentration of the pollutant in question at the recipient. That is, instead of taxing and monitoring emissions, the load to a recipient is taxed and monitored.

In a seminal paper by Montgomery (1972), the theoretical workability of an ambient-differentiated emission permit system is demonstrated. The author analyzes two systems of marketable pollution permits: a system of “pollution licenses” that defines allowable emissions in terms of pollutant concentrations at a set of receptor points and a system of “emission licenses” that directly grants the right to emit pollutants up to a specified rate. Montgomery shows that a system of “pollution licenses” generates a market equilibrium that coincides with the least-cost solution for attaining any predetermined level of environmental quality regardless of initial allocation of licenses among polluters.

Krupnick *et al.* (1983) propose a pollution-offset scheme, in which sources of emissions are free to trade emission permits subject to the constraint of no violations of the predetermined air-quality standard at any receptor. This scheme is a modification of Montgomery’s (1972) system of emission licenses. Their suggestion is a hybrid of both the emission- and the ambient permit systems. The authors criticize Montgomery’s policy (1972) based on the unrealistic conditions under which it works, as well as for excluding the role of transaction costs, which they claim are likely to be quite high for his system of pollution licenses. The offset-scheme is claimed to be preferable over other systems with regard to minimizing total abatement cost as well as transaction costs. The authors define permits in terms of emission and allow their sale among polluters but not on a one-to-one basis (Emission permit system character), thereby implying a spatially differentiated emission based system. Transfers of permissions are only allowed if the air-quality standard at any receptor point is not violated. Like the emission permit system, it involves the purchase and sale of permits but like the ambient permit system, the ratio at which permits exchange for one another depends on the relative effects of the associated emissions on ambient air quality at receptor points. According to the authors, Montgomery’s requirement that any transactions among polluters result in no increase in pollutant concentrations at any receptor point, is unnecessarily restrictive, and generates an outcome that will not coincide with the least cost solution. They conclude that the trading equilibrium under the offset system coincides with the least-cost solution irrespective of the initial allocation of emission permits. Like the ambient permit system, a suitable designed offset system can achieve the predetermined standards for air quality at the least cost for any initial allocation off emission permits, but this system would require less transactions. An advantage of this system, according to the authors, is that it makes modest demands regarding transaction costs of sources as well as administering agency.

Segerson (1988) questions the feasibility of direct regulations of emission levels, such as effluent charges, from nonpoint source pollutants due to monitoring difficulties and uncertainties, and calls for policy instruments focusing on the ambient quality instead. According to the author it is impossible to neglect the physical uncertainty in the linkage between abatement and damage, as well as the stochastic relationship between discharge and ambient pollution level. She proposes an incentive scheme involving a linear tax/subsidy and lump sum fixed penalty/subsidy based on the observed deviation on the ambient pollution concentration from a target. Segerson emphasizes the difficulties to relate the ambient quality to the actions of an individual polluter in the presence of many polluters. To eliminate the problem of free-riding, she suggests a uniform tax over all sources equal to the marginal damage. According to Segerson, such a scheme requires little government interference, guarantees long-run efficiency, eliminates free-riding, and only requires monitoring of the ambient pollutant level.

Horan, Shortle, & Abler, (1998) criticize Segerson’s assumption that the distribution of emissions is determined by a single variable, *i.e.* abatement. They prove that Segersons’ linear ambient tax scheme only works in the special cases where less than three production decisions influence emissions or when there are no risk effects associated with the use of different inputs. They extend Segerson’s scheme by exploring the design of ambient taxes when the distribution of each source’s emissions, which are stochastic and not directly observable by firms or the regulator, depends on the polluter’s choices over a set of variables. The authors suggest a linear and non-linear ambient taxes depending on the environmental state of the receptor. Uniform state dependent linear ambient taxes are here determined ex post optimal since, unlike the state-independent tax, polluters have an incentive, at the margin, to consider the impact of each input on expected damages. However, even in these special cases, additional instruments may be needed to ensure that the long-run efficiency condition is satisfied.

In a more recent paper, Horan, Shortle, & Abler, (2002) extend the analysis by considering the design of ambient taxes for risk-neutral and risk-averse polluters under asymmetric information about environmental relationships and probabilities associated with random events. The authors show that a linear ambient tax in which the tax rate on the ambient base is state-independent can be efficient only when the covariance between marginal damage and the marginal effects of firms’ choices on ambient pollution is zero for all firms and inputs. They emphasize the information requirements for both firms and agency, and that the benefits of ambient based instruments are lost when polluters and the regulatory agency have asymmetric information and heterogeneous expectations about nonpoint pollution processes, and when some polluters are risk-averse. The authors come to the conclusion that optimal ambient taxes must be differentiated in the presence of asymmetric information about environmental relationships and probabilities associated with random events. They also propose a firm-specific lump-sum tax/subsidy in order to obtain long-run efficiency. To require firms' choices to be monitored along with ambient pollution levels would generally increase the transaction costs of an ambient system. According to the authors, a linear ambient tax with a state dependent rate equal to marginal damages, and a nonlinear ambient tax where each firm pays an amount equal to total damages can induce efficient input choices.

An extension to the work by Segerson (1988) and Horan *et al.* (1998, 2002) is given by Hansen, (2002), in which he introduces stochastic dependence of firm emissions being restrictive since common stochastic effects, such as weather, may cause covariance in firms' emissions. Hansen proposes a linear variance based tax for small number stochastic non-point pollution problems where the damage function is convex. Such policy eliminates the need for firm level information and rate differentiation, while retaining implementation in dominant strategies according to the author.

Comparative analysis of efficiency losses between different policies

The main argument for a certain type of policy is its ability to achieve the ambient target at least-cost. Not surprisingly, therefore, several empirical studies have focused on estimating and comparing the cost of different polices under different circumstances. However, few of these studies have included the transaction cost related to the policy in question, implying that the resulting deviations in costs between two policies must be regarded with caution.

Kneese (1971a) applies the theoretical framework of Russell-Spofford in connecting pollutants with the damage they cause in a case study regarding the management of several waterborne pollutants to the Delaware estuary. The author estimates the costs of a uniform charge and a uniform reduction and compares them with the cost of a cost-effective solution. Kneese's results indicated large cost differences between uniform cutbacks and cost minimization, but small between uniform charge and cost minimization. The author also discussed the problems of the present policies of this time in achieving an optimal allocation of abatement, such as the fact that border of significance for regional pollution problems *(e.g.* watersheds) rarely coincide with the jurisdictional borders of management. He promotes effluent charges over subsidies and encourages the role of regional agencies.

Atkinson & Lewis (1974), compare the cost of a policy that is cost-effective at source (*e.g.* a uniform effluent charge) with the present policy in the U.S. at that time referred to as the state implementation plan (*i.e.* a uniform reduction standard at sources), and compares these costs to a policy that ensures cost-effectiveness at recipient. The approach is static in that it targets the average level of ambient concentrations of sulphur dioxide across air-shed, in the St. Louis air quality control region. Their results indicate that annual total regional control cost of the state implementation plan is as much as ten times larger than those for the cost-effective policy. The authors find that a policy only cost-effective at source is twice as costly as the policy cost-effective at recipient.

The procedure to find the optimal effluent charge proposed by Baumol-Oates is applied in a paper by Herzog, (1976). The author compares the cost of three different policies with the cost of a cost-effective policy of reducing Biochemical Oxygen Demand (BOD) and nitrogen discharges to the Patuxent river of Maryland (U.S.). The cost of a weighted charge, i.e. differentiated between regions, is in this case 6 percent higher than the cost-effective, while the cost of a uniform charge is 22.2 percent higher. Finally, the policy of a uniform percentage treatment turns out to be 29 percent higher. Herzog uses a tatonnement procedure to determine the uniform charge as well as the different weighted charges required in order to reach the target.

Two classes of permit markets, emission based permit system and ambient permit system, are compared in an article by Atkinson & Tietenberg (1982). The former system includes two types of spatially differentiated permits while the latter includes three types of multiple zoned emission permits, where trading across zones is prohibited. The objective of their study is to determine how these two different markets and their modifications affect the air quality of multiple receptors, emissions, and costs. The empirical study concerns the particulate control of the St. Louis air quality. Compliance costs, as a function of permit design, are included in their cost estimates. Their result shows that all permit designs cause lower compliance cost at all levels of control than the current State Implementation Plan (SIP) approach, focusing on non-transferable emission standards. Cost advantages of the ambient permit systems are explained by the fact that they allow substantially more emissions while achieving the ambient target. The disadvantage of the ambient permit market is its complexity, requiring each source to generally have to purchase several of the receptor-oriented permits. Their results indicate that for all permit designs, permit expenditures are more than half of total cost for less severe degrees of control but they become a less significant proportion of total cost as the degree of control is increased. The authors claim that all policies except the pure ambient permit policy create incentives for an emission source to locate within the same area, a so-called hot spot problem. The authors find advantages and disadvantages with all policies, which leads to their suggestion of the possibility of a policy, which is a hybrid of all the different designs in this study.

Mendelsohn (1986) analyzes pollution regulation in the presence of heterogeneity in benefits and costs. He emphasizes the possibilities of improvements by a thorough examination of how to optimally differentiate environmental standards across pollutants and space. The findings of Weitzman’s (1974) paper ‘Prices vs. Quantities’ are used with regard to unobserved variations in the benefits of abatement from heterogeneous polluters. The purpose of the paper is to examine how regulations ought to adapt to the heterogeneity of emissions as well as the heterogeneity of environments. Mendelsohn considers multiple trading regions as he develops and applies a model for differentiated tradable permits among pollutants and source locations. The author compares the cost of a uniform market, in which the trading ratio between permits is on the one-to-one basis, with five different degrees of differentiated markets regarding sulfur dioxide bubble markets of coal-fired power plants in Connecticut (see Mendelsohn, 1980). Mendelsohn shows that marginal benefits of spatial differentiation drop as the degree of this differentiation increase. In accordance with Tietenberg (1973a), Mendelsohn states that the optimal degree of spatial differentiation is found where the marginal reduced loss of an additional degree of spatial differentiation equals its marginal administrative cost. He also deals with how efficiency losses are affected by the distribution of sources and impact. Mendelsohn points out that any presence of skewness has implications on the efficiency loss of uniform policies. One possible way of achieving a more effective degree of spatial division would be to simply create a single zone for those regions corresponding to this fat tail of distribution. In Mendelsohn's case, variation in marginal costs as well as covariance of marginal benefits and marginal costs affect the choice over a price instrument or a quantity instrument, while variation in marginal damages does not directly influence this choice.

Krupnick (1986) compares the cost of five different policies: an ambient marketable permit policy (i.e. least-cost spatially differentiated policy), a policy where emissions trading is restricted to sources of the same type (regardless of location), a uniform effluent fee irrespective of source type and location, a command-and-control policy, and finally a command-and-control/least cost hybrid. Costs are estimated for meeting the nitrogen dioxide standards in Baltimore from a multiple type of sources. In Krupnick's study a uniform fee turns out to be eight times as costly as a spatially differentiated least cost policy due to severe over control, while a source type specific fee is only four percent more costly.

Tietenberg (1988) provides a summary regarding the result of nine studies estimating the efficiency losses of command-and-control policies in comparison to least cost policies aimed at air pollution control. These results indicate additional costs of command-and-control policies in comparison with a cost-effective solution ranging in order of magnitude from 1.07 to 22.

Using four different sediment transport models over agricultural pollution Braden *et al.* (1989) compare estimated costs of least-cost abatement regimes in a central Illinois case study. The optimal allocation of abatement measures depends on which of the four models is used. The authors find that substantial heterogeneity regarding the locations of abatement measures accentuates the desirability of spatial differentiation with regard to agricultural pollution. However, they acknowledge implementation problems with a targeted management regime, due to difficulties in capturing transport models.

Howe (1994) gives a review of the implementation and success in Europe of different policy standards. He supports the claim that a uniform effluent tax will not achieve the social optimum in the presences of varying marginal damages. The author finds that minimum cost is only guaranteed using multiple zones if the diffusion process is linear.

In a study by Brännlund & Gren (1999), a comparison of costs between a uniform and a differentiated charge for reducing the nitrogen load to the Baltic Sea caused by fertilizers is made. The costs are estimated for a 20 percent and 50 percent reduction respectively, considering correlation in input demand elasticity and marginal environmental impacts between regions. The efficiency loss of a uniform policy corresponds to 17 or 10 percent of the costs of a differentiated charge depending on the environmental impact target.

Driving factors behind efficiency losses of uniform instruments under spatial heterogeneity

The explanation of the underlying factors determining the magnitude of cost differences between different polices under spatial heterogeneity has been the subject of several articles.

The objective of Kolstad (1986) is to understand the characteristics of regulatory alternatives for ambient air pollution control. The alternatives compared are: price control vs. quantity controls; spatially differentiated vs. uniform controls; and command-and-control regulations vs. economic instruments. The author includes uncertainty on the part of the regulator in the empirical model. By making plant location endogenous the industrial responses to regulation is also incorporated into the model. The area studied is the “Four Corners” region of the Southwest United States and the pollutant of concern is sulfur dioxide. He makes the comparisons for four differently shaped damage functions: linear, sublinear, superlinear and kinked. This shape determines whether price control is preferred over quantity controls, spatially differentiated over uniform controls; and command-and-control regulations over economic instruments. Efficiency losses of uniform policy, for example, are proven to increase significantly as damages become superlinear, and becoming twice as costly than an efficient control for a kinked damage curve. The effect ambient air regulations have on the U.S. economy, as a whole, is also accounted for in this study.

In a purely theoretical paper Kolstad (1987) sets out to determine how the slope of the marginal cost and benefit functions determines the degree of efficiency losses under uniform instruments. Kolstad’s results indicate that the least error (in a welfare sense) from adopting uniform instruments is associated with linear costs and benefits and the most error is associated with sharply curved costs and benefits (i.e., steep marginal costs and benefits). It is therefore of importance to determine the shape of these curves and what parameters they are a function of, in order to determine the efficiency gains of spatially differentiated policy instruments.

Including a dynamic parameter to the problem Bouzaher, Braden, & Johnson, (1990) obtain results indicating the efficiency gains of applying spatially differentiated policies, increase as pollution limits are tightened. Braden, Larson, & Herricks (1991), emphasize, in a case study, how administrative costs increase with higher degrees of spatial differentiation making the advantages of spatially differentiated policy instruments less pronounced.

An approach to estimate the efficiency losses of different policy instruments using the summary statistics of a few variables is developed by Newell & Stavins (2003). In this article, the heterogeneity parameters causing the efficiency losses of uniform instruments are identified and analyzed. The authors identify the underlying factors generating the inefficiency of uniform policies for three types of policies two of which are uniform and one a cost-effective charge. Their estimates are obtained by applying Taylor approximations on quadratic abatement cost functions. They provide a theoretical analysis of how cost savings of market based polices changes with the heterogeneity in emissions and marginal abatement costs. Their model is applied on nitrogen oxides emissions from electrical utilities in a group of Eastern United States, obtaining estimates that indicate cost savings of a market-based policy to be 51 percent in comparison to a uniform emission rate standard respective 44 percent in comparison to a uniform percentage reduction standard. The authors show how increased regulatory flexibility can yield increased cost savings, and the extent of such savings depends on the degree of heterogeneity.

Gren (2004) compare a regulator's net benefits under uniform and differentiated policies taking into consideration an asymmetry in hidden information regarding the farmer's abatement cost. The farmers are separated, with their respective probability, depending on whether they are low or high cost types. Gren shows that the relative advantages of a differentiated policy depend on the slope of cost and benefit functions as pointed out by Kolstad (1987), as well as the covariance between marginal abatement cost and the derivative of land use with respect to type. When, in absolute terms, the change in marginal environmental benefits is larger (smaller) than the change in marginal provision costs, a differentiated policy generates larger (smaller) expected net benefits than a uniform policy' (p70). A linear abatement cost function implies higher net benefit under the differentiated policy than under the uniform. She applies the theoretical method on wetland creation, reducing the nutrient load, in the Laholm Bay drainage basin located in the southwest of Sweden. Due to the linear abatement cost function of wetland a differentiated policy generates net benefits four times larger than a uniform.

Nationally vs. locally determined effluent charges

A debate took place in the *American Economic Review* in the seventies regarding whether ambient targets should be determined on a national or local level. Even though this debate concerned the administrative aspect of ambient quality policies, it touched upon the same issues as the discussion above. The debate especially discussed the transfer coefficient of the pollutant transport from source to the recipient and the generated benefits of reducing the damage on a recipient of concern.

Stein (1971) criticizes the president's council's argument that effluent charges should be set locally, and argues that a uniform charge on pollution should be determined on a national level. His point is that if environmental amenity belongs to the U.S. as a whole, the marginal product of the environment should be the same everywhere and therefore regulation cannot be differentiated as long as the environment is regarded as a national good. This article became the subject of much criticism and starts a debate that would last in the *American Economic Review* for six years.

The first attack on Stein came from Kneese a year later (1972), who questions Stein’s proposal of nationally determined charges. Kneese’s argument is based on the fact that the damage function of a pollutant might differ geographically, depending on natural factors, implying that a uniform regulation of emissions can never be the first-best solution. Instead, charging a dollar for a dollar’s worth of damage requires quite different rates of charge per pound of discharge depending on the locality, according to Kneese. Peltzman & Tideman (1972) join the discussion by stating that Stein’s article contains logical errors. They argue that Stein ignores the essential spatial aspects of the pollution problem, fails to distinguish between the desirability of a single price and that of having a single price setter, and fails to distinguish between the relevant short and long runs’ (p.959), thereby also introducing the dynamic aspect into the debate. Only under very unrealistic assumptions can a nationally uniform pollution charge be optimal in the long run, according to the authors.

In 1974, Lerner enters the debate, and criticizes Stein, arguing that Stein seems to confuse ‘a unit of pollution, in some physical sense, with a unit of pollution damage which ultimately can only be a subjective evaluation’ (p.716). On the other hand, he agrees with Stein that a charge of pollution damage must be uniform nationally, but since it is only the local population that feels the damage, he sides with Kneese (1972) that ‘the only national principle to be laid down is that a dollar’s worth of pollution damage must be charged a dollar’ (p716). In Stein’s (1974) response, he makes it clear that it is the pollution damage that should be subject to a uniform national price and not the pollution itself, thereby allowing for different prices per pollution in different localities. He acknowledge that “the distinction is not sufficiently clear” in his previous article. However, Stein does not agree with Lerner that it is only the local population that feels the damage of pollution, since there can clearly be spill over effects since the environmental goods in that region might be a public good for all residents in the nation, whether they live in that region or not.

Menz & Miller (1977) discuss whether uniform nationwide prices for pollution damage are necessary for economic efficiency. They argue that Stein’s result is based on a rather restrictive specification of the social welfare function that does not allow for differences in regional preferences for environmental quality. In the presence of such differences, nationwide uniformity of prices for pollution damage is unlikely to be efficient, even when environmental quality is a national public good. They develop a model showing that at any point in time, the existence of environmental spill over from one locality to another is not a sufficient condition for nationwide uniformity of pollution damage prices.

In the final article of the debate, Lerner (1977) characterizes the dispute between himself and Stein as involving a minor and a major issue. The minor issue concerns the distinction between charging pollution or pollution damage, while the major issues relate to whether charges should be determined on a national (Stein’s position) or local level. Regarding the minor issue, he argues that the problem lies in the different definition of pollution damage between them. Lerner claims that Stein’s pollution damage is a physical argument in the utility function, since he argues for a uniform charge per unit decrease increase in the impurity of water.

Each separate act of pollution must be judged and charged according to the damage to the utilities of the people affected. No physical measure can substitute for this. The major issue, whether charges should be determined on a national, cannot be resolved without empirical proof that everybody in the nation is damaged by every externality.

Questions answered and raised in the quest for an optimal policy under spatial heterogeneity

As can be seen from the literature, the quest for an optimal policy has been going on for a while. At first, the complex nature of reaching an ambient target under spatial heterogeneity was in focus. How to determine the optimal target and stringency of pollution abatement policy in the presence of externalities across administrative borders was discussed in the seventies. It has also been debated whether to focus on an ambient quality target policy or a policy targeting the emissions at source. Some articles have questioned the feasibility of market based policy instruments and effluent charges in particular. The role of the transfer function between source and recipient, its implications regarding the choice of policy has been discussed thoroughly. The literature provides several empirical studies comparing the costs of different policies under different settings and in different cases, the majority of them finding significant efficiency losses of uniform policies. Lately, the discussion has evolved around the factors causing the efficiency losses of uniform policies. Not much work has been done regarding the transaction costs related to cost-effective differentiated policies.

The quest for an optimal policy aimed at an ambient target is likely to continue, considering that an agreement concerning the most preferable policy hasn’t been reached. One answer behind this might be that the optimal policy depends on the characteristics and complexity of the spatial aspects of the environmental problem studied. The papers of this thesis tackle the complexity of managing a recipient in the presence of spatial heterogeneity cost-effectively. A major part of this thesis is to link abatement cost at source with the damage of the recipient of concern. This thesis provides empirical comparison of costs for different policies, cost-effective as well as uniform. The identification and analysis of parameters explaining the efficiency losses of uniform policies are extended in this thesis. Especially how the shape of the marginal abatement cost curve, at source as well as recipient, and the transfer coefficient, affects the efficiency losses of different uniform policies is described. How uncertainties in the transfer coefficient, between source and recipient, affects the allocation of emission abatement as well as the policy instruments is also accounted for.

Scope of the research

This thesis focuses on the cost-effective managing of a coastal zone in the presence of spatial heterogeneity regarding emission sources. By adopting a source-recipient approach and applying it to the region studied, a cost-effective allocation of abatement measures is determined. Estimating the cost of different policy options and analyzing the underlying factors behind these costs provides important insights in the quest for the least-cost strategy.

A main characteristic of all four articles is the presence of spatial heterogeneity regarding the transformation of the pollutant in question on its trajectory from source to recipient. Together with any heterogeneity of marginal transaction costs at the source, this calls for the need of spatially differentiated policy instruments in order to obtain a cost-effective allocation of abatement. As mentioned before, the three first articles of this thesis are applied to the nitrogen load into the Stockholm Archipelago, which is a coastal zone of the Baltic Sea, degraded by eutrophication.

The same theoretical model is used in the empirical part of all four articles in order to obtain estimates regarding costs of abatement as well as different policy instruments. This model, connecting emissions from sources with the damage they generate at the recipient as well as taking the interdependency between abatement measures into consideration, is used for determining a cost-effective allocation of abatement measures. In article II, the estimates of this model are compared to the estimates of a model able to approximate cost estimates using less information. In article III the model is used to estimate the efficiency losses of uniform policies. In article IV the model is applied for a smaller part of this coastal zone, Himmerfjärden, and its adjacent catchment area consisting of four drainage basins.

General questions to be answered

Apart from connecting the cost of abatement with the benefits they generate at the recipient, there are three major questions to be answered by the articles of this thesis. The objective of article I is to answer the question: what is the efficient nitrogen load to the Stockholm Archipelago and by what allocation of abatement measures should it be reached? Article II aims at answering the question whether cost approximations as developed by Newell & Stavins (2003) are accurate in estimating cost differences between uniform and cost-effective policies. How different policy instruments differ with regard to cost and what explains these differences are the questions to be answered by article III. Article IV answers the question on how the cost-effective allocation of abatement of reaching a nitrogen reduction target to marine waters is effected by including the uncertainties of pollutant transport, and the buffering capacity of coastal basins.

Summaries of articles

Article I – The efficient management of eutrophic coastal zones in theory and practice: an application of nitrogen reduction to the Stockholm Archipelago

To connect nitrogen abatement cost with the benefits generated in the Stockholm Archipelago in order to determine decision rules for efficiency and cost-effectiveness is the first task of article I. Such connection is vital in order to determine the efficient nitrogen load to this recipient. The methodology of this article resembles that of Gren (1993), Gren *et al.* (1997). The article considers four different abatement measures: reduced application of fertilizers, cultivation of catch crops, wetland construction, and reduced nitrogen discharges at wastewater treatment plants using best available technology. The interdependency between these abatement measures is included in the model. The river basin of the Stockholm Archipelago is divided into 33 drainage basins differing with regard to abatement cost, nitrogen transport and abatement capacity.

Data from 1998, when possible, were used. Since the underlying assumption of a constant marginal benefit curve can be questioned, a decision rule for reaching either the valued 1-meter water transparency improvement or the politically determined 50 percent reduction target is also accounted for. Results are, therefore, obtained for three different decision rules. The conditions for differentiated charges and tradable permits, triggering the cost-effective allocation of abatement are also described in this article.

Results indicate that there are substantial gains to be made by reducing the nitrogen load to the Stockholm Archipelago. By definition, the largest gains, 524 million Swedish crowns (MSEK) per year, are obtained at a nitrogen load level where marginal costs of abatement equals marginal benefit, i.e. efficiency in abatement (8.9288 SEK = 1 Euro, 1998). This implied a reduction of the load by 51.2 percent, a reduction that differs little from the politically determined 50 percent reduction, which in accordance generated gains differing insignificantly (MSEK 523/year). A 1-meter water transparency improvement requires a 40 percent load reduction and generated annual gains of MSEK 443.

For any significant reduction level, abatement by wastewater treatment plants as well as reduction of fertilizer application from farmed lands are necessary. Construction of wetlands is only required for reduction targets exceeding 40 percent while catch crops cultivation only should be implemented for reduction targets over 50 percent. The present policies, to a large extent characterized by uniformity and somewhat arbitrarily set abatement requirements, would not be able to achieve any reduction target cost-effectively. Instead, a spatially differentiated policy instrument is required in order to ensure that the market solution is equivalent to the cost-effective allocation of abatement measures.

The article raises the question of exactly how much is to be gained by spatially differentiated policy instruments in comparison with a uniform policy.

Article II – Comparing two approaches of estimating costs of uniform and spatially differentiated policy instruments

Article II can be seen as an extension on article I regarding the role of spatial heterogeneity in the quest for the optimal policy. However, the main objective of this article is to determine how the cost approximations developed by Newell & Stavins (2003) performs in estimating the cost of a uniform and a spatially differentiated tax on fertilizers in the Mälar region in comparison to actual estimates using a full-data set. What makes the cost approximations of Newell & Stavins's method attractive is that they require only certain summary statistics in order to estimate costs of different policy standards. Another attractive feature is that they provide some important insights to the explanatory variables behind the efficiency losses of uniform policies.

The theoretical approach in the article is based on the model developed by Newell & Stavins. But, while they considered heterogeneity in marginal abatement cost at the source, this article deals with heterogeneity of marginal abatement cost to the recipient being a function of marginal abatement cost at source as well as the impact these sources has on the recipient. The article also includes the presence of capacity constraints regarding the abatement measure in question. Abatement cost is estimated for a spatially differentiated charge on fertilizers as well as one requiring a uniform percentage reduction of emissions from fertilizers using their approach. These estimates are then compared with the abatement cost of the two different policies obtained from a complete data-set. Only abatement by fertilizer reduction is considered as a measure while the three other abatement measures of article I are excluded since cost approximations cannot be estimated for abatement measures characterized by constant marginal abatement cost, which is an assumption made concerning the cost functions of these measures. Efficiency losses related to the present uniform tax on fertilizers, are also estimated using the full data set, but analyzed using the cost approximation expressions.

The results of this article indicate that Newell & Stavins’s method is successful in estimating the cost of a cost-effective spatially differentiated tax on fertilizers. However, the presence of capacity constraints causes the approximation of the cost-effective case to be less accurate under more stringent reduction targets. The cost approximations of a uniform charge overestimated the actual cost to a larger extent, which could be explained by the underlying assumptions of this method. The article shows that the present uniform tax on fertilizers of SEK 1.80 Kg/N implies annual efficiency losses of MSEK 2.12 in comparison to a cost-effective solution.

Article III - Efficiency losses of uniform policy instruments in the presence of spatial heterogeneity of marginal abatement cost

The comparison of costs between different policy instruments continues in article III, but includes the other three abatement measures into the empirical application. Costs here are estimated by a measure-by-measure programming using the complete data-set. This article separates the abatement cost to recipient of article II into its two components; abatement cost at source and impact on the recipient by emission. Three different types of uniform instruments are in this article compared to the cost-effective spatially differentiated policy instrument (SDPI). These three uniform policies are: uniform charge on emissions for all sources, uniform percentage reduction by sources as well as a uniform percentage reduction by regions, in this case the drainage basins. Sources are wastewater treatment plants and farmed land and their emissions are nitrogen leakage from the root zone for the latter and discharges into a body of water for the former. The article shows that efficiency losses related to uniform policies to a large degree is explained by the variance in emissions, slope of marginal abatement cost curve at source, and impact on recipient as well as the covariance between these three. Efficiency losses of a uniform charge are explained by variance in impact and any covariance between impact and the slope of the marginal abatement cost curve. Variations in emissions and slope of marginal cost curve at source have no influence on the cost of this policy since it is cost-effective at source.

Results indicate significant efficiency losses of the uniform policies. A policy requiring each source to reduce their emissions by the same percentage comes out as approximately twice as expensive than a cost-effective SDPI for most reduction targets. A uniform percentage reduction by regions is 50 percent more costly, while a uniform charge is around 30 percent more expensive.

Article IV– Cost effective management of stochastic coastal water pollution

By including the probability of reaching the target into the decision rule, article IV takes into consideration the uncertainty in reaching a predetermined load due to the stochastic nature of the pollutant transportation. Article IV shows how the presence of uncertainties regarding the transport of pollutants affects the cost of reducing the nitrogen load to a recipient. The nitrogen transport in-between the different water basin of Himmerfjärden and its implications for the decision rule of reaching a targeted load to the Baltic Sea are also included into the model. In a stochastic approach, such as this, the impact of abatement measures on both the mean and the variance of the pollutants load to a recipient are of interest. Therefore, the pollutant transport from land to the coastal zone is considered to be a stochastic variable.

Costs are estimated for a 50 percent reduction in the nitrogen load from Himmerfjärden to the Baltic Sea, based on the Helsinki ministerial agreement (Helcom, 1993). The 50 percent reduction target can be reached at different probabilities ranging from 0.5 to 1, where 0.5 represents the case when variations in pollutant load have no impact on the decision problem. In this setting, the allocation of abatement measured within a drainage basin is determined by the marginal costs, expected marginal decrease in pollutant loads, risk attitudes as expressed in the choices of probability, coefficient of variation, and the changes in variances of pollutant loads. The exchange of the pollutant between different coastal basins, also considering their respective buffer capacity, is included into the model since it has an effect on the pollutant load to marine waters. Whether or not the consideration of coastal transport implies a higher total cost for a given marine water target depends on the relation between marginal costs of pollutant reductions to the coastal basins and the coastal water transport coefficients. How to design market based policy instruments, charges and permit trading ratios, in this model setting is also discussed.

The theoretical model is applied on Himmerfjärden and its drainage basins, situated somewhat southwest of the Stockholm Archipelago. Himmerfjärden is divided into four coastal basins as defined by sea bottom thresholds. These coastal basins work as a nitrogen sink with respect to the load entering the marine water of the Baltic Sea, which is implied by the fact that only 1/3 of the nitrogen load entering the coastal basins ends up in the Baltic Sea. Two targets are used in this article, with and without consideration for these coastal transports, for reducing nitrogen the nitrogen load to the Baltic Sea from the drainage basins of

Himmerfjärden. Nitrogen abatement is done at wastewater treatment plants, by reducing the application of fertilizers, and construction of wetlands. Of these measures, only wetlands affect the variations in nitrogen transport, and will, therefore, influence the decision rule under a stochastic approach. To reduce the nitrogen load to the coastal waters by 50 percent, implies a minimum cost of 8.3 millions SEK (MSEK), while the cost to reduce the nitrogen load to the Baltic Sea by the same fraction only costs 6 MSEK. Considering coastal transports of nitrogen, the total cost of reaching the targeted load to the Baltic Sea is reduced by at least 20 percent.

Main contributions of articles

The main contributions of the four articles of are mainly empirical conclusions for this region regarding the efficient load of nitrogen to the Stockholm Archipelago and the costs for different policies in achieving this and other targets.

Article I suggests that there are potential gains to be made by decreasing the nutrient load to the Stockholm Archipelago. The article emphasizes the necessity to link marginal abatement cost with marginal benefits in order to determine an efficient coastal zone management. This implies the importance of reliable information when dealing with spatial heterogeneity. The allocation of abatement measures for reaching any of the three targets suggests the necessity to focus on measures with large impact on the load and relatively low marginal abatement cost at the source. Further, it shows how present policies are not cost-effective and unable to reach the efficient load.

Article II gives some support to the method developed by Newell & Stavins (2003) of estimating costs of policy instruments using summary statistics. The article shows that their model can be applied to an ambient reduction target. However, it is shown that this method should be used with caution especially in the presence of significant heterogeneity, capacity constraints, and large reduction targets. The article shows a negative effect on the accuracy of these estimates when capacity constraints are met. With significant differences in marginal abatement cost it is likely that sources with low marginal abatement cost should reduce as much as possible even for small reduction targets. Article II also gives an estimate regarding the efficiency losses of the current uniform tax on fertilizers.

The main contribution of article III is to enhance the understanding of how the choice of policy affects total abatement cost. The article provides conclusions concerning the inefficiency of different types of uniform instruments under spatial heterogeneity, and some guidelines with regard to choosing a second-best policy. The article also provides insights concerning the underlying factors of efficiency losses for all three uniform policies. Results indicate that for this region, the efficiency losses of a uniform charge are not substantial, which might be explained by a negative covariance between the slope of the marginal abatement cost curve and impact on the recipient. The differences in costs between uniform over sources and uniform over regions, gives some insights regarding potential efficiency losses of international agreements where each participating country is required to reduce its emissions of a certain pollutant by the same percentage.

Article IV show that costs of reducing the nitrogen load to the marine waters of the Baltic Sea change dramatically when considering stochastic pollutant transports and including coastal nitrogen transports. Including the coastal transport of the pollutant into the model lowers total costs of reaching a target, due to the buffering capacities of the coastal water basins. By considering the random impact together with the assumption of risk-averse attitude or convex damage functions a higher total pollution reduction requirement for the recipient is necessary, implying higher costs than if only expected outcomes are considered. Including the abatement measure's effect on the variations in load also affects the cost-effective allocation of these measures. If wetlands increase (decrease) the variance in the load their value as abatement measure decreases (increases) relative to a measure only affecting the expected load. This value is enhanced for higher probabilities of reaching a certain target. This article emphasizes the importance of taking uncertainties regarding the transport coefficients into consideration in the quest for a cost-effective management of coastal zones.

Suggestions for future research

Due to data constraints, several assumptions and simplifications have been made with regard to the cost and benefit functions used in the thesis. Some topics for future research are simply found by relaxing some of the underlying assumptions.

Cost functions are used to predict how actors respond in their behaviour to changes in input or output factors. Some of the cost functions of this thesis could clearly be questioned on the basis of underlying assumptions. One such assumption in this thesis is that everything is compensated for in the economy except nitrogen, which is made for the sake of simplicity. To relax this assumption and include other market imperfection regarding prices or presence of non-efficient subsidies and/or taxes could be subject for further research. The assumption of a constant marginal benefit curve regarding the improvement of water transparency in article I, has implications regarding the reliability of the efficient load level obtained. Significant improvements could be made in the case study by estimating the slope of the marginal benefit curve of improved water transparency. Such an extension would generate more certainty regarding the Pareto-optimal nitrogen load. A closely related extension would be to separate the recipient into several basins, differing with regard to impact by load and willingness to pay for abatement. Including phosphorus into the analysis is of great importance as shown by Elofsson (2003), as well as the interaction between the two nutrients.

There are uncertainties related to the data used in the articles due to the assumptions made as well as the impossibility to obtain models that describes relevant natural processes perfectly. The effect of uncertainties could be added to article I, especially regarding uncertainties of reaching the target due to the temporal variability of the buffering capabilities from source to recipient (see *e.g.* Charnes & Cooper, 1963; Elofsson 2003; Fishelson, 1976; Adar & Griffin, 1976; Papakyriazis & Papakyriazis, 1998).

Article II and III could be extended by relaxing the assumption concerning normal distribution regarding the underlying parameters explaining the cost differences between different policies. Any presence of skewness and kurtosis of the relevant parameters would have implications on the efficiency losses of uniform policy as shown by Mendelsohn (1986).

The role of transaction costs regarding the policies discussed is also excluded in the analysis of the articles. However, to incorporate transaction costs into the empirical application of the articles requires extensive data collection, which is beyond the scope of this thesis. To determine the true cost of achieving a certain reduction target with regard to the nitrogen load to the Stockholm Archipelago is impossible without including the transaction cost of implementing the policy in question. There are a number of, theoretical as well as empirical, studies made concerning the transaction costs of different policy instruments (see *e.g.* Atkinson & Tietenberg, 1982; Linder & McBride, 1983; Colby, 1990; Malik *et al.*, 1993; Stavins, 1995; McCann & Easter, 1999; Braden *et al.*, 2001; Netusil & Braden, 2001; Kampas & White; 2002; Zylicz, 2003; Elofsson, 2003). An analysis of transaction costs would be most interesting to include regarding the analysis of article III. The challenge would be to determine what kind of transaction costs that changes with different policies and by what extent. Such analysis would be of significant importance in the quest for an optimal policy aimed at ambient targets under spatial heterogeneity.

The choice in policy does not only stand between uniform and spatially differentiated policy instrument, as pointed out by Tietenberg (1978). A policy can be implemented for several different degrees of spatial differentiation, and a uniform charge represents merely the extreme case of zero spatial differentiation. The degree of spatial differentiation increases with the number of regions within a given area. An increased degree of spatially differentiated policy instrument reduces the cost of reaching the target, disregarding transaction costs (see Mendelsohn, 1986). To what degree a policy can be spatially differentiated depends on the availability of necessary data. The empirical work of this thesis has only considered one degree of spatial differentiation, i.e. a spatially differentiated policy over 33 regions. Another objective of future research would, therefore, be to compare the cost of a uniform policy (one region) with the cost of different degrees of spatially differentiated policy instrument, i.e. differentiated over different number of regions. The results regarding different policy instruments abatement costs in reaching a certain target have relied on the assumption of perfect compliance. How the enforcement of compliance should be made under a spatially differentiated policy instrument is a question interesting to focus on in future studies.

This thesis only considers the damage caused by one pollutant, nitrogen, on one recipient, the Stockholm Archipelago, and ignores any upstream damage or damage on the Baltic Sea. Another topic for future research is, therefore, to include multiple recipients with different limiting nutrient (nitrogen or phosphorus), and separate targets (for studies regarding multiple receptors see *e.g.* Atkinson & Tietenberg; 1982; Krupnick *et al.*, 1983; Bohm & Russell, 1985; Krupnick 1986; Ermoliev *et al.*, 1996, Zylicz, 2003;). How the exchange of nutrients between this coastal zone and the surrounding waters influence the efficient level of reduction is another topic for future research.

The analysis of this thesis excludes the dynamic aspect of the problem in that it takes a static perspective, implying that it disregards the time lag between an abatement measure and its effect on the recipient. For a discussion concerning the dynamic aspect with regard to ambient quality targets see Segerson (1988) Horan *et al.* (1998, 2002), and Hart (2003).

The geographical scale for which a case study is done have vital implications regarding the required information. For a small study area certain parameters might be disregarded since they might exhibit small variations in value for the area in question. For example, information concerning meteorological factors might be important when looking at national and international problems, while this parameter can be excluded for areas of smaller size, such as a river basin, since the meteorological variations might be insignificant within such a small geographic area.. In the case study area of article IV, that is a relatively small geographic area, data of leakage from specific crops were available and used instead of treating the leakage from agriculture as a function of applied amount of fertilizers only. It would be interesting to find out how data requirements change as the geographical scale of the study becomes either larger or smaller.

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