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Eutrophication reduction from a holistic perspective

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Abstract

Single measures that are implemented in order to reach some goal often have effects on other goals as well. In this paper, we look at the Swedish environmental goal *Zero eutrophication*, and the two interconnected sub goals of nitrogen and phosphorus reduction. Measures that are taken in order to reduce nitrogen often have an effect on phosphorus emissions, and vice versa. Thus, the cost efficient set of measures has to be identified by analyzing how to reach both goals simultaneously. The paper maps the set of possible outcomes that a policy maker could choose from, and discuss how that choice could be informed by an environmental index (EI). The paper also discusses the benefits of, a priori, formulating the eutrophication goal in terms of an EI instead of, as today, in terms of separate nitrogen and phosphorus reduction goals. Finally, we suggest an eutrophication index and discuss how the results in the paper, based on very crude data, nevertheless could have a practical use.

1. Introduction

The European Union´s Water Framework Directive (WFD; European Parliament, 2000.) requires that most waters achieve "good ecological status", specified as *"only a slight departure from the biological community which would be expected in conditions of minimal anthropogenic impact"* (European Commission, 2010), by 2015. The environmental quality is, however, allowed to stay below good ecological status if the costs are deemed unreasonably high compared to the benefits. In order to achieve the goal, the current status of different waters has been determined, and measures that could be taken in order to improve that status have been identified. In Sweden, the problem with the by far most expensive suggested measures is that of human induced eutrophication. In the Northern Baltic Sea water district (which is one of Sweden's five water districts) alone, the suggested measures are expected to cost SEK 670 million (about 100 million USD). Eutrophication is primarily caused by leakage of the nutrients nitrogen (N) and phosphorus (P), and Sweden has separate goals for each of these nutrients. The importance of those goals are, however, largely instrumental in the sense that there is little value in e.g. a reduction of N-loading by itself. Instead, the value of a reduced N-loading comes from its effect on eutrophication, which in turn depend on the P-loading. Thus, the issue at hand is what measures that should be taken in order to reach the eutrophication target(s), and how much of these measures that should be directed towards N and P reductions respectively.

The first objective of this study is to identify the subset of measures that should be implemented, within the northern Baltic Sea region, in order to reach a cost efficient fulfillment of the two separate nutrient reduction goals that the overarching eutrophication goal today exist of. An interesting, and complicating, feature that has to be accounted for is that measures directed towards N reductions also have an effect on P emissions, and vice versa. This interdependence implies that we should analyze how to reach both goals simultaneously, rather than perform separate analysis for each goal. The cost of achieving multiple goals might be much cheaper (or much more expensive) than the sum of the costs associated with the fulfillment of each separate goal (cf. Geijer et al. 2011). In addition to the changes in total cost, there might be changes in the marginal costs, and thus the welfare maximizing level of the goals, as well as in the relative value of different actions.

It is, however, questionable whether there should exist two separate sub goals to start with. If we are interested in eutrophication, and eutrophication depends on N and P, there might be many combinations of N and P that imply the same level of expected eutrophication. Thus, we will argue, there also exists an interdependence between the goals in the sense that the desired level of P should depend on the acquired level of N, and vice versa. This type of interdependence can be formalized through an environmental index (EI) that allows for aggregation of the single parameters, in this case N and P, into a single measure of environmental quality, in this case eutrophication. The environmental index allows us to calculate the cost of reaching a specific environmental quality goal, or level of eutrophication, rather than the cost of reaching specific N and P emission targets.

A secondary objective is to use this example to make a broader point about actions that have an effect on multiple goals, and the tradeoff that usually has to be made between those multiple goals as long as we do not have enough resources to fulfill them all.

The reminder of the article is organized as follows. Section 2 provides a more detailed background to the problem, as well as a literature review. Section 3 describes the measures that could be implemented in order to reduce nutrient emissions. It also shows the marginal cost, total cost and side effects/synergies associated with reductions of either nitrogen (N) or phosphorus (P) emissions. Next, in section 4, we find the cost minimizing set of measures that would fulfill the targeted N and P reduction, and compare it with the currently proposed combination of measures. Here, we also analyze whether sequential goals concerning P and N reductions would be significantly more expensive than a framework that takes P and N into account at the same time. If our sole aim were to fulfill the currently stated goals for N and P reduction, the analysis could end here.

The sections that follow are about finding, exploring, analyzing and formulating "better goals". In section 5, we obtain the budget sets, i.e. the combinations of N and P reductions that are possible to achieve at different total costs. In section 6, we develop three hypothetical environmental indexes. The EI allow us to aggregate N and P reductions into a single environmental quality measure, which enables us to talk about the cost of reducing eutrophication (rather than the cost of reducing N or P). Naturally, the change of goal function has an effect on the cost as well as on the choice of measures. In section 7, we argue that the actual goals concerning eutrophication should be replaced by such an EI. In section 8, we discuss how information from a centralized cost minimization process, lacking relevant information, could be combined with more decentralized, and likely different, information. The final section contains a discussion and some concluding comments.

Section 4 is relevant for cases where individual measures have an effect on multiple goals, even if those goals are considered incommensurable. While the budget sets in section 5, strictly speaking, are pointless if the goals are incommensurable - we still think that it is rather uncontroversial to suggest that the decision maker should have a rough idea about what they look like when formulating the goals[1]. Finally, section 6 and 7 are worth considering when it is reasonable to explicitly quantify the tradeoff between the different goals – and should be completely uncontroversial when, as often is the case in Swedish environmental policy, the goals are instrumental with respect to the actual goal.

2. Background

Eutrophication is mainly caused by phosphorus (P) and nitrogen (N), which in turn enters the water through both natural and anthropogenic causes. Basically, there are two types of phytoplankton: nitrogen-fixing cyanobacteria (Aphanizomenon, Nodularia) that are able to use nitrogen from the atmosphere and other phytoplankton. As long as both P and N are available in the water, the other types of phytoplankton have an advantage to the nitrogen-fixing cyanobacteria. When the loading of nitrogen in the water is almost completely consumed but phosphorus still is abundant, the nitrogen-fixers gain a competitive advantage (Kiirikki et al., 2003). Thus, at the margin, only one of the two substances is the limiting factor for biological growth of the other types of phytoplankton, and thus the determinant for the amount produced. If, at that point, there still exist a substantial amount of P, it might lead to growth of cyanobacteria. Thus, if P is the limiting factor, N reduction is less beneficial than if N itself were the limiting factor. Reductions in N might, however, still be useful since

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[1] In our experience, the claim that different goals are incommensurable generally emerges from an aversion to explicit quantification of their relative importance rather than from an actual claim that every Pareto efficient solution is equally valuable.

emissions of N in a P-limited environment to some extent increase the stock of N in the system. If less N is stored in the sediment and water, fewer actions might be needed later if the system turn N-limited (or, similarly, future P reductions might have an effect it otherwise would not have). For example, the Stockholm archipelago, which is within the northern Baltic sea region that we will analyze in this paper, probably shifted from a N-limited to a P-limited ecosystem sometime in the 1970s due to changes in the N:P ratio of nutrients entering the archipelago, although it is hard to say which one that limits growth today. One reason as to why it is hard to say which nutrient that limits growth is that P from bottom sediments is assumed to be a substantial, although not fully quantified, source of current P loading (Boesch, 2006).

Eutrophication is certainly not a new problem. In Sweden, concerns arose in the 1960s about long term trends in declining oxygen concentrations and its potential impact on fish habitats (Boesch, 2006). Negative ecological impacts associated with eutrophication are, among other things, decreased biodiversity and changes in species composition and dominance. Effects that are more visible to the broad public include toxicity caused by cyanobacteria, which sometimes have led to closure of recreational waters, and reduction in water transparency, which generally is seen as an unaesthetic property. Later on, in year 1999, when the Swedish parliament accepted 15 long term environmental quality goals (which later turned into 16 goals), *Zero Eutrophication* was one of them. Since then, many studies have tried to put a value on the reductions of eutrophication. In Sweden alone there are, among others, e.g. Östberg et al. (2011), Fransen (2006), Söderqvist (2000 and 1996) and Frykblom (1998). On the cost efficiency side, Scharin (2005 a, b) and Brady (2003) both show why uniform fees or regulations will fail to create cost efficient solutions due to spatially dependent damage functions. Another study from Elofsson (2004) argues that the actions taken against eutrophication, with a cost of SEK 800 million (120 million USD), were twice as expensive as the most cost efficient ones. There are also cost benefit analyses, e.g. Kinell (2012), who analyses whether a large sewage treatment plant close to Stockholm should reduce its emissions of nitrogen, and conclude that they should.

The Swedish environmental protection agency have investigated whether the Swedish reductions in emissions of nitrogen and phosphorus to the Baltic Sea could be achieved through tradable emission rights but conclude that, at least in the short run, only about 25 percent of the nitrogen and 15 percent of the phosphorous reductions that are required according to the Baltic Sea action plan (HELCOM, 2008) could be expected to be achieved this way (SEPA, 2010). In the long run they see some potential for inclusion of further sectors, accounting for a few additional percent of the total emissions, at the price of increased transaction costs.

The already mentioned studies generally either only focuses on nitrogen or phosphorus, treat them separately or assume that both types of nutrients is reduce by some fix proportion. A report from the Nordic Environment Finance Corporation (NEFCO, 2008) suggest that there should be single market for N-equivalents, where P could be valued according to the so called Redfield ratio[2], where a kg P reduction is seven times more valuable than a kg N reduction. However, the SEPA (2010) study mentioned above reject such a fixed ratio solution, primarily due to the fact that Sweden, in accordance with the Baltic Sea Action plan, has separate goals for P and N reductions. As already mentioned, the environmental quality goal *Zero Eutrophication* also contains separate sub goals concerning N and P reduction. Instead, the EPA report suggests that separate markets should be created for nitrogen and phosphorus (ibid.). It goes on by stating that;

"*The agency will face a complex problem in determining how the costs should be distributed between P and N reductions when a measure creates both types of reductions"* (SEPA 2010, page 56, translated by the author).

Another SEPA study, *Default Monetary Values for Environmental Change* (Kinell et al, 2010), conducts a meta analysis of different valuation studies of eutrophication in order to find appropriate values for reductions in phosphorus and nitrogen. However, since some of the valuation studies don't specify how the reduction of eutrophication would be achieved, and thus to what extent the valuation should be tied to reductions in nitrogen and/or phosphorus, Kinell and coauthors have to make those assumptions themselves – and proceed by assuming that the valuations are entirely related to either the loadings of

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[2] The Redfield ratio is the atomic ratio of carbon, nitrogen and phosphorus (C:N:P = 106:16:1) found in plankton and throughout the deep oceans. In terms of weight, 16 N atoms weigh seven times more than one P atom.

nitrogen or to the loadings of phosphorus. In Hökby et al (2003), another meta study, the valuations associated with the same valuation studies are assumed to be related to N reductions alone.

There are, however, also previous studies that focus on multiple, interacting, pollutants in general and on P and N with respect to eutrophication in particular. Theoretical papers on multiple, interacting, pollutants includes Endres (1985) and Ungern-Sternberg (1987) with analyses of the problem in a static framework – and Moslener & Requate (2007) and Kuosmanen & Laukkanen (2011) with analyses of the problem in a dynamic framework. The lmost recentof those papers, i.e. the one by Kuosmanen & Laukkanen (2011), focuses on under what conditions we will receive a corner solution in the sense that we only should focus on the abatement of one of the pollutants. One of their examples is eutrophication, where they point out that if algae growth can be modeled by a Leontief function, the optimal solution will always be a corner solution. Economic studies that focuses on Swedish nutrient reduction policies while simultaneously taking both N and P reduction into account includes e.g. Elofsson (2006), who argue against the current N and P goals in favor of a focus on either P or N (depending on how much euthropication should be reduced), and Elofsson (2012) which, among other things, argue for less geographical restrictions in where (particularly P) abatement can take place. Hyytiäinen et al. (2013) conducts an cost benefit analysis of emission targets that span the entire Baltic Sea region, and concludes that there are reasons to change the goals as well as in which geographic area abatement should take place. Their conclusions also suggest that almost all (94 percent) of the benefits could be achieved at a small part (17-31 percent) of the cost associated with a complete fulfillment of the BSAP goals.

Finally, there isa study commissioned by the Swedish Board of Agriculture: *Synergies In the Environmental Work – How to Make Cost Benefit Analyses When the Measures have Effects on Multiple Goals?* (Holstein, 2011), where the fact that many of the measures taken to reduce N or P, reduces both N and P, is the object of the analysis. The report evaluates different ways of picking measures from a set of potential measures in order to fulfill a required level of P and N reduction, and show that the most cost effective subset is chosen by linear programming. The analysis in section 4 of this paper is very similar to some of the analysis that is done in Holsteins report. While Holsteins report focuses on the environmental goal *Zero Euthropication*, it is primarily meant as an general example of what to do when individual measures has effects on multiple goals.

There also seem to be a move towards more holistic environmental goals and strategies within the EU. While earlier directives had names such as “the Nitrate directive (1991)” or “the Waste-Water Treatment Directive (1991)”, they now have names such as “the Water Framework directive (2000)” and “the Marine Strategy Framework Directive (2008)”. At the same time, or because of this (see e.g. Dworak and Pielen, 2006), Swedish agencies have shown interest in conceptual discussions and practical guidelines about how they should deal with actions that have an effect on many policy areas or goals at the same time[3]. Thus, it does seem to have caused an increased awareness about the fact that some actions have effects on many goals at the same time[4]. If true, it is not very surprising since e.g. the Water Framework Directives (WFD) programmes of measures, containing the actions needed in order to reach the required level of ecological status in all bodies of water, has to take all the effects into consideration at the same time - while the implementation of earlier directives, e.g. the waste water directive, could limit the analysis to a narrower set of outcomes.

As already mentioned, a secondary objective of this study, as with Holsteins report, which it is inspired by, is to use this example as a case study for actions that have an effect on multiple goals as well as the tradeoffs between those multiple goals. Unlike the theoretical papers mentioned above - who mainly focuses on the properties of the optimal solutions from a centralized optimization – we try to take things a bit slower, even though we a priori know that we will end up suggesting the same type of model. More specifically, we imagine a situation where we are faced with a decision maker (or, more realistically, a working group, stake holders and different decision makers) where we have to make the picture of the available tradeoffs, and the potential benefits of making use of them, as clear as

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[3] The research program “PlusMinus”, which provides funding for this study and is sponsored by the Swedish Environmental Protection Agency, is one example. A list of additional reports and studies is available from the author on request.

[4] The causation could, and of course does, to some extent go in the other direction as well. I.e. the attitude change came before the change towards more holistic directives, at least within the communities that influence environmental regulations on the EU level.

possible. Sweden has, for example, a system of 16 overarching environmental goals, with each goal containing many sub goals – but there is an almost complete lack of explicit tradeoffs between those environmental goals (and between those environmental goals and other social goals as well). In the few cases where tradeoffs are explicitly mentioned, they are general explicitly forbidden (i.e. the worst variable decides the outcome – as in the ecological status of waters according to the Water Framework Directive). More specifically, Sweden still aims at a balanced nutrient abatement with separate goals for N and P, even though the studies mentioned above finds it suboptimal. It could still, however, be useful for a policy maker to see how measures taken towards one goal have an effect on other goals (as in section 3) or the available policy space (as in section 5), in order to get a clear picture of the fact that there exist tradeoffs that could be considered. Another (maybe complementary, since it slices the data differently) way to show the existence of tradeoffs is to simply state a few (reasonable) objective functions who allow different levels of substitutability between the goals (e.g. Eloffson, (2006). She state the CES goal function that she thinks best represent the ecological (eutrophication) production function but also provide a sensitivity analysis with many different values of the parameter for the elasticity of substitution). We do this in section 6, but also argue that the existence of a goal function might be important as a communication tool and as a way to know where we should go in the short run, in addition to its role in identifying the long run optimal solution. In section 7 we point out that it might be reasonable to allow for some substitutability even if we know that the ecological production function is a Leontief function. In the same section, we also suggest what an eutrophication index could look like. The point of section 4 is mainly to show that it would be more expensive to fulfill one goal at a time than both at the same time. We also find the cost minimizing set of actions, but that has relatively little practical value since, fitstly the data is hardly complete and, secondly there is no way for the social planner to decide what that should be done in any great detail anyway (except for relatively large projects). However, in section 8 we do claim that the results could be used as guidance for other policy actions.

While this study take both N and P reductions into account, the analyzed measures certainly have other significant effects as well. E.g. the creation of wetlands will probably have an effect on the emissions of greenhouse gas, biodiversity, and maybe recreation as well. In section eight, there will be a largely qualitative discussion about considerations of non-modeled effects. While this study won’t go very far, and only includes two effects, the general framework and approach could easily be extended to include additional effects.

3: Measures and data.

As already mentioned, this article is inspired by Holstein (2011) – and will also use the same data[5]. This data differ from the data described in the Northern Baltic Sea programme of measure (LVl, 2009) in the sense that the later present the effect of some measures by a mean value accompanied by an interval. Holstein instead assumes that 20% of the activities belong to the more beneficial extreme of the interval – i.e. are more effective/cheaper than the mean, that 20% belong to the least effective/most expensive category, and that 60% have characteristics similar to the reported mean[6]. Thus, while the programme of measures state that e.g. “*P-dams, more efficient*” will have a mean effect on P reduction of 37.5 kg/year, but that individual dams will be in the interval 50-25 kg/year, Holsteins data put 20 percent of the available actions at an effect of 50 kg, 20 percent at 25 kg and 60 percent at the mean effect.

Holsteins report mentions 23 types of measures for N and P reductions, shown in table 1. The column “*MaxCap”* refers to the amount of available measures of a particular type, while the column “*proposed*" shows the subset of measures that are proposed in the programme of measures. As can be seen, the programme of measures suggests that almost all of the inventoried measures should be implemented. The exceptions are about 10,000 measures for removal of phosphorus in industrial and sewage treatment plants and 3000 measures concerning individual sanitary sewers.

Since the measures in the table 1 are presented at a lower level of aggregation than in the programme of measures, we have to assume how the Northern Baltic Sea water agency would split their suggested actions among the sub categories. Concerning phosphorus removal in industrial and sewage treatment plants, the measures in category one and two Pareto dominate those in category three, and we can safely assume that they would choose

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[5] The data on measures are taken from table 6, page 76, in Holstein, 2011.
[6] Holstein based these assumptions on personal communication with different agencies and experts.

the better measures. It is, however, difficult to a priori say which category of individual sewers that is the “best”, and we will initially assume that they omit a thousand measures from each category. Later on, when we know which subcategories of individual sewers that are the “best” ones, we will include an alternative cost calculation under the assumption that they would have chosen to implement the best subcategories of individual sewers. The columns *N-red* and *P-red* stand for the nitrogen and phosphorus reductions achieved by implementing the measure in question. Information concerning how e.g. one time investment costs are taken into account in order to calculate the yearly cost can be found in the Northern Baltic Sea programme of measures (LVl, 2009).

Table 1. Measures from the Northern Baltic Sea programme of measures

Nr	Measure	N-red (Kg./year)	P-red (Kg./year)	Cost (SEK./year)	MaxCap	Proposed
	P-dams more effective				480	480
1	I	40	50	17458	96	96
2	II	40	37,5	17458	288	288
3	III	40	25	17458	96	96
	P-dams, less effective				320	320
4	I	20	12,5	26142	64	64
5	II	20	7,5	26132	192	192
6	III	20	2,5	26132	64	64
7	Protective zone, more efficient	7	0,66	2800	4550	4550
8	Protective zone, more efficient	7	0,26	2800	11375	11375
	Wetlands, more efficient				1900	1900
9	I	200	25	6000	380	380
10	II	40	6	17000	1140	1140
11	III	10	1	28000	380	380
	Wetlands, less efficient				2400	2400
12	I	3	3,5	34000	480	480
13	II	3	3	34000	1440	1440
14	III	3	2,5	34000	480	480
	Sewage plants + industry N				2650000	2650000
15	I	1	0	22	530000	530000
16	II	1	0	60	1590000	1590000
17	III	1	0	330	530000	530000
	Sewage plants + industry P				47900	37900
18	I	0	1	150	9580	9580*
19	II	0	1	3100	28740	28320*
20	III	0	1	6600	9580	0*
	Individual sewers				20000	17000
21	I	4,5	1	3500	4000	3000*
22	II	5,29	1	7000	12000	11000*
23	III	7,5	1	11800	4000	3000*

*Distributed over subcategories according to assumptions in text.

N-red and P-red stand for nitrogen and phosphorus reductions.

If all the listed measures were to be implemented, we get a total nitrogen and phosphorus reduction of 3031 and 118 tonnes per year, at a total cost of SEK 756.2 million. The proposed actions would result in an emission reduction of 3013 tonnes of nitrogen and 105 tonnes of phosphorus at a total of SEK 669 million.

The majority of the measures have an effect on the emissions of both nitrogen and phosphorus. Figure 1 A and 1 B shows the marginal and total cost of reductions in nitrogen emissions (without regard to side effects/synergies). The synergy effect "free phosphorus" – i.e. the reduction of phosphorus that would be a side effect of the implementation of the most cost efficient measure against nitrogen emissions - is shown in figure 1 C. Figure 2 A-C show the same things for the most cost efficient reductions in phosphorus emissions (with reductions in nitrogen as the side effect). With a goal concerning moderate N reductions alone, we would get rather small reductions in P. Almost all P reductions do, however, also reduce N emissions. Together, this implies that two sequential goals, starting with some N reductions and then demanding P reductions, would be more expensive than taking both goals into consideration at the same time.

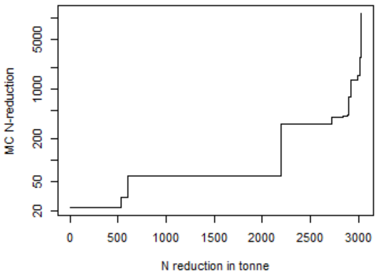


Figure 1.A: MC in SEK/kg N reduction

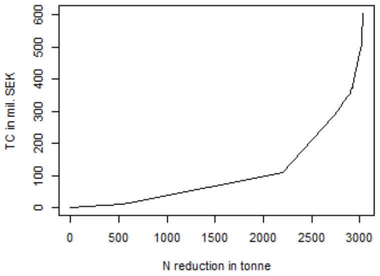


Figure 1.B: Total cost

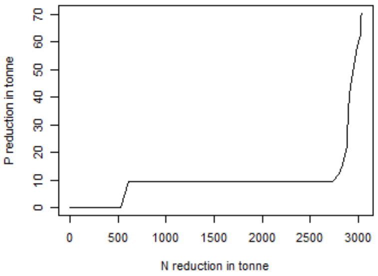


Figure 1.C: Free P reduction

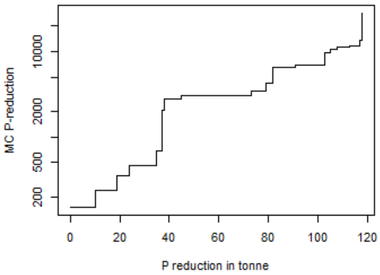


Figure 2.A: MC in SEK/kg P reduction.

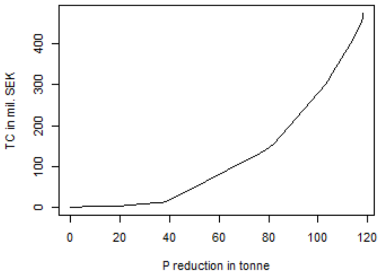


Figure 2.B: Total cost

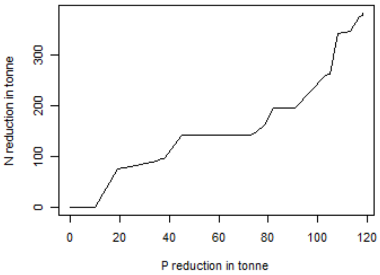


Figure 2.C: Free N reduction

4: Cost minimization – finding the cheapest way to achieve the goals

As Holstein (2012) points out, the cost minimizing mix of measures can be obtained by linear programming. More specifically, it is the solution to the problem:

$$Min\ f(\boldsymbol{a}) = \boldsymbol{Cost^T} * \boldsymbol{a} \qquad (1)$$

s.t.

$$\boldsymbol{Pred^T} * \boldsymbol{a} \geq \bar{P} \qquad (2)$$

$$\boldsymbol{Nred^T} * \boldsymbol{a} \geq \bar{N} \quad (3)$$

$$\boldsymbol{0} \leq \boldsymbol{a} \leq \boldsymbol{MaxCap} \quad (4)$$

Where ***Cost***, ***Pred***, ***Nred*** and ***MaxCap,*** are vectors containing the cost, nitrogen and phosphorus reductions and the maximum possible number of implementations associated with each type of measure in Table 1. $\bar{P}$ and $\bar{N}$ refer to the amount of required phosphorus and nitrogen reductions and ***a*** is a vector of free variables.

As already mentioned, the “proposed” measures in table 1 would cost SEK 669.3 million and result in N and P reductions of 3013 and 105 tonnes. A cost efficient combination of measures would, however, achieve the same nutrient reductions at a cost of SEK 623.9 million – i.e. SEK 45.4 million, or 6.7 percent, cheaper.

At the cost efficient solution, the shadow prices of N and P is SEK 693 and 6600 per Kg respectively. At these shadow prices, individual sanitation sewers of the first and second subcategory (measures of type 21 and 22 in table 1) are “better” than those in the third subcategory, in the sense that their effect is valued higher than their cost, while the effect from sewers of the third kind exactly match their cost. If we assume that the Northern Baltic Sea Water Agency intended to implement all measures concerning individual sanitation sewers in subcategory one and two, but only one thousand measures in subcategory three, the total N reduction would be 5.2 tonnes smaller while the total cost would decrease by 13.1 million to SEK 656 million. The minimum cost associated with the same nutrient reduction is SEK 620 million – i.e. SEK 36 million less than the suggested measures.

In order to see the cost difference between sequential and simultaneous goals, we set $\bar{N}$ to 1507 tonnes (and $\bar{P}$ to zero) and find the cost minimizing vector of measures, $\boldsymbol{a}^*_{\bar{N}}$**.** Next, we change $\bar{P}$ to 52.5 tonnes and replace the lower bound in the last inequality of equation 4 by $\boldsymbol{a}^*_{\bar{N}}$. Finally, we minimize the cost of achieving $(\bar{P}, \bar{N})$, given that the measures in $\boldsymbol{a}^*_{\bar{N}}$ has to be choosen**.** We do the same thing starting with P reduction, and finally minimize the cost of achieving $(\bar{P}, \bar{N})$ simultaniously. The results of this exercise is presented in table 2.

Table 2, Cost Minimization

Scenario $(\bar{P}, \bar{N})$	Cost suggested 1 (3013,105)	Cost min (3013,105)	Cost suggested 2 (3008,105)	Cost min (3008,105)	Seq N, P (1507,52.5)	Seq P,N (1507,52.5)	Cost min (1507,52.5)
Cost	669	624	656	620	123	119	119

Cost suggested 1: cost of the suggested measures in table 1.

Cost suggested 2: as in 1, but with an alternative mix of individual sewers measures.

Seq i,j: sequental cost minimization – starting with i.

As expected, sequential cost minimization starting with N reduction is more expensive (by SEK 4 million, or 3.4 percent) than taking both goals into consideration at the same time. However, at the specified goal,sequential cost minimization starting with P reductions would be as cheap as simultaneous cost minimization.

The data used in this paper is very coarse and while the SEPA, in connection to their suggested cap and trade scheme mentioned in the beginning, suggest that we should disregard inland concentrations of nutrients in favor of reaching cost efficient nutrient reductions to the sea – others might argue that we should look at eutrophication of inland waters as well. Whether the nutrient status of inland water is taken into account or not, a more complete analysis would also have to take retention into account. If we assume that the effects described in table 1 is the effects on nutrient emissions into the closest body of water, and that a particular measure would decrease emissions far upstream in a river, the effect on the sea will often be smaller than if the same emission reductions were acquired in a coastal area. As already mentioned, this is the focus of some previous cost efficiency studies such as Scharin (2005 a, b), Brady (2003) and Elofsson (2004). Models concerning retention of P and N in inland waters can be found on the *Swedish Environmental Emission Data* homepage (www.smed.se), but require that we know the location of the measures (something that we are likely to know prior to the final implementation). Given such data, the set of cost minimizing actions could be obtained in much the same way as the results above (see appendix A). The thing we want the reader to note in the model described in appendix A is the large number of hard limits, i.e. the number of “greater then” signs, it introduces to the analysis. As long as we view the goals in this uncompromising way, each single goal should be fulfilled no matter what. If this is how the final analysis would be done, it would be of the outmost importance to also report the shadow values of each constraint, and thus give an estimate of the marginal cost associated with the individual goals.

Another shortcoming in the data is that it only focuses on measures that have a direct effect on the point emissions into waters within the Northern Baltic Sea region. The effect of e.g. the reduction in a specific source of airborne emissions on a specific water district, or even worse, a specific body of water, is hard to measure. Even if we were able to measure it, it would probably be hard to motivate any restrictions with respect to the effects on the single water district alone. This implies that different types of measures sometimes have to be analyzed on different scales. A discussion about how to integrated analyses done on different scales can be found in e.g. Dworak et al. (2006).

5: Budget sets/isocost lines – finding the policy space.

In section four, we found the set measures that would fulfill the stated goals at the minimum cost. From this point and onwards we will take a step back and think about whether it was the right goals, or the right type of goals, to start with. Ideally, the social planner wants to take a look at the tradeoffs before a goal is determined. If the number of goals is equal to or less than three, the tradeoffs can be visualized graphically. However, usually a fourth goal can be written as a function of three others, which allow a graphical visualization of four goals through a three dimensional level sets. If there are more than three (or four) goals, you either need to use vectors or hold something constant in order to produce a graph. In this case, we will only concern ourselves with three goals, N and P reductions and cost, and a two dimensional diagram will suffice. More specifically, we want to visualize the possible N and P reductions that are available at different levels of cost.

In order to acquire the possible combinations of (N,P) reduction we note that for every point ***x*** on the boundary of a convex set, there exist a supporting hyperplane containing ***x***. The question then becomes whether it is reasonable to think about the possible (N,P) combinations associated with each level of spending as convex set, and how to find the supporting hyperplanes.

The set of possible (N,P) reductions will be convex if any two vectors of measures that are possible given some level of spending, say $a_{R',\bar{C}}$ and $a_{R'',\bar{C}}$, reducing emissions by $(N_{R',\bar{C}}, P_{R',\bar{C}})$ and $(N_{R'',\bar{C}}, P_{R'',\bar{C}})$, imply that we also can chose a convex combination of the measures. Of course, this is not always strictly true. For instance, while it might be possible to create 0.362 ha of wetlands, it might be unwise to only partly finish a dam. However, given the number of measures that we are dealing with in this case, this is hardly a concern – and we will therefore assume that the set of possible (N,P) reductions is convex.

The supporting hyperplanes are also easy to find. In order to do this, we start by defining a scale factor *"R"* $(0 \leq R \leq 1)$ which set the relative weight of N, in comparison to P, reduction. If R is equal to one, we only care about N reductions and if R is equal to zero, we only care about P reductions. We choose an R and the maximum amount of resources that can be spent on measures (*MaxCost)*, and maximize the linear programming problem:

$$Max\ f(\boldsymbol{a}) = R * \boldsymbol{Nred^T} * \boldsymbol{a} + (1 - R) * \boldsymbol{Pred^T} * \boldsymbol{a} \qquad (5)$$

s.t.

$$\boldsymbol{Cost^T} * \boldsymbol{a} \leq MaxCost \qquad (6)$$

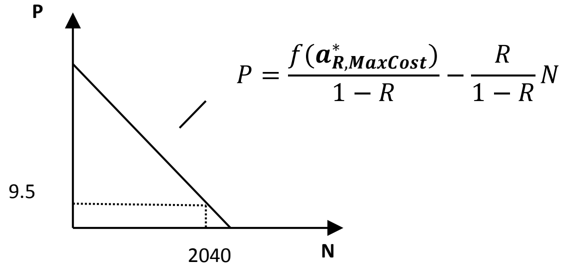
$$\boldsymbol{0} \leq \boldsymbol{a} \leq \boldsymbol{MaxCap} \qquad (7)$$

Where ***Cost***, ***Pred***, ***Nred*** and ***MaxCap*** are vectors containing the cost, nitrogen and phosphorus reductions and the maximum possible number of implementations associated with each type of measure in Table 1. We save the vector of optimal measures, $\boldsymbol{a}^*_{\boldsymbol{R,MaxCost}}$ and calculate the N and P reductions by:

$$N(\boldsymbol{a}) = \boldsymbol{Nred} * \boldsymbol{a}^*_{\boldsymbol{R,MaxCost}} \qquad (8)$$

$$P(\boldsymbol{a}) = \boldsymbol{Pred} * \boldsymbol{a}^*_{\boldsymbol{R,MaxCost}} \qquad (9)$$

To exemplify, if we allow SEK 100 million of spending, and assign N reductions twice the value of P reductions (R=2/3) in the objective function, we get N and P reductions of 2040 and 9.5 tonnes. Since this nutrient reduction maximizes our objective function we know that all other possible combinations of measures would result in a lower or equal value of the objective function. Thus, if there existed a possible combination of N and P reductions above the solid line[7] in figure 3, the chosen combination would not have been the one that maximized the objective function. The solid line creates an outer bound of the N and P combinations that are available at a cost of SEK 100 million or less, i.e. it gives us a subset of those N and P combinations that definitely are unavailable at that cost. We do not know which combinations below the line that are possible but, given free disposal, we do know that we can get all the combinations below the dotted line which constitutes our inner bound.



$$P = \frac{f(\boldsymbol{a}^*_{\boldsymbol{R,MaxCost}})}{1-R} - \frac{R}{1-R}N$$

Figure 3. Phosphorus (P) and Nitrogen (N) reduction

Next, we keep the maximum spending at SEK 100 million, vary R over a few different values, and solve the maximization problem for each R, in order to acquire figure 4.

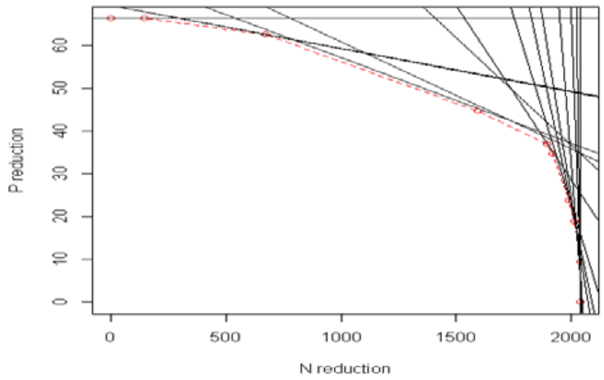


Figure 4: Budget set associated with SEK 100 M in

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[7] The solid line is acquired by substituting equation 8 and 9 into equation 5, the objective function, and solve for P.

As in figure 3, we know that we cannot achieve any point outside the solid lines, and since we know that we are dealing with a convex set we can achieve any convex combination of the cost minimizing solutions associated with different values of R (described by the dotted line). The area between the outer and inner set is small, even though we used relatively few R values.

More formally, the set of possible actions defined by the outer and inner bound is:

$$Outer(\bar{c}) = \{N,P|\ RN + (1-R)P > f\left(a_{R,\bar{c}}\right) \forall R \in \mathcal{R}\} \qquad (10)$$

$$Inner(\bar{c}) = \{N,P|\ (N,P) \leq \lambda\left(N\left(a_{R',\bar{c}}\right),P\left(a_{R',\bar{c}}\right)\right) + (1-\lambda)\left(N\left(a_{R'',\bar{c}}\right),P\left(a_{R'',\bar{c}}\right)\right)$$

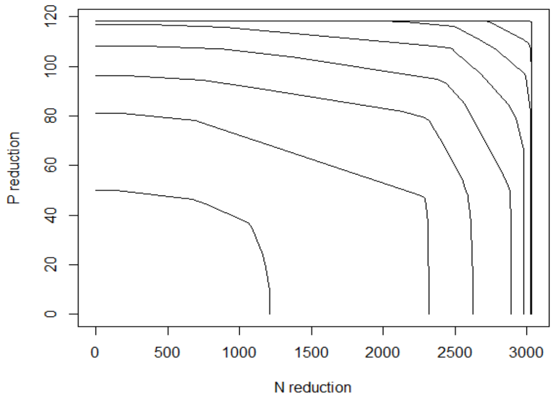
$$for\ any\ two\ R \in \mathcal{R},\ \lambda \in [0,1]\} \qquad (11)$$

Where $\bar{c}$ stand for a fixed *MaxCost* and the set $\mathcal{R}$ denotes some set of numbers between, and including, zero and one. As the set of numbers in $\mathcal{R}$ expands to include all numbers in the interval, the complement of the set defined by the outer bounds and the set defined by the inner bounds will be identical.

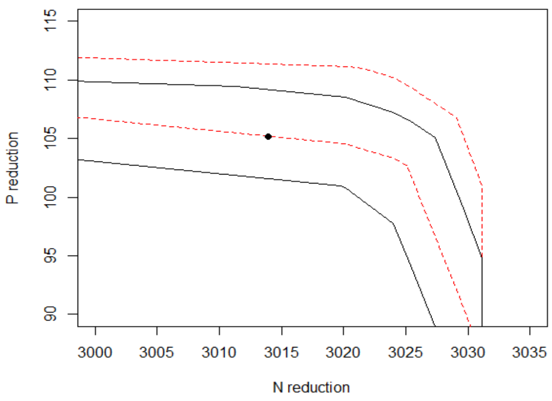
The budget sets in figure 5 is created in the same way as those in figure 3 and 4, but this time we let R take one thousand different values with respect to each level of spending, and only present the set defined by the inner bound.

Figure 6 also show four budget sets. The dot shows the reductions associated with the *suggested* measures in table 1. The suggested measures are, however, 45 million Sek. more expensive than necessary (according to the calculations in the previous section) – and the outer dotted line show the reductions that would be possible at a spending level equal to the cost of the suggested measures (i.e. cost = 669 million). The inner dotted line, which passes through the dot, show the different combinations that would be possible at a level of spending equal to the minimum cost of achieving the suggested nutrient reduction (i.e. cost =623 million).

Figur 5: Isocost lines: 50 milj, 150 milj, 250 milj ... 750 milj



Figur 6: Isocost lines: 669 milj, 650 milj, 623 milj and 600 milj.



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The slope of the 623 million Sek. isocost line, at the suggested reduction, is 0.105. In order for this point to be optimal, the value of a marginal tonne P reduction has to be 9.5 times as valuable as a tonne N reduction. This is slightly higher than the Redfield ratio suggested by the Nordic Environment Finance Corporation (NEFCO, 2008) which, as mentioned in the introduction, put a seven times higher value on P reductions – but far less than the 33 times higher relative value suggested by the meta study by Kinell et al (2010). However, the main point is that the construction of these isocost lines allow the decision maker to grasp the full spectrum of available alternatives.

6. Environmental index – more than a goal.

In the previous section, we looked at a graphical representation of the possible goals that a social planner could choose from. The goal might, however, be a long term goal, and many years might pass before it is completely fullfilled. It is also possible that we never reach the desired endstate. In the first case, we might want to aim at the best possible intermediate nutrient reductions in order to get the most, if not all, environmental improvements as soon as possible. In the second case, the need of implementing the most efficient subset of the initially planned reductions is even more obvious. The existence of a set of goals do not, in themselves, tell us anything about which partial fullfillments of those goals that are viewed as more favourable than other.

The absense of explicitly formulated tradeoffs of this kind is a very common shortcomming in the formulation of Swedish environmental goals. As previously mentioned, Swedish environmental policy is to a large extent centered around sixteen environmental quality goals. The goals were, however, decided upon some time ago (in year 1999) and according to the timeline, they should be fulfilled by 2020. According to the latest comprehensive evaluation (SEPA, 2012), only one of the sixteen environmental quality goals will be fullfilled by that time, given presently implemented or planned policy tools. Of course, Swedish environmental policy will continue after 2020 as well, but given the long time it takes between the formulation of the goals and their fullfillment (if ever), you would like information about more than the desired endstate, which in itself do not give any information about intermediate priorities. That we, say, know that the final goal is 3012 and 105 tonnes of N and P reductions do not tell us whether 2000:50 or 1000:70 tonnes of N:P reduction is a prefereble intermediate position. To be fair, the Swedish Environmental Protection Agency (and other agencies involved in the environmental work) do submit all more extensive policy initiatives to a cost benefit analysis, but this is usually done in the end of the policy process. If the goals, as intended, are to be able to guide the policy work (as well as providing early signs for those that soon might be affected by e.g. regulations or taxes) – they have to provide some information about what is deemed desirable, e.g. create the “best” environment, in the short term and not only what the end state should look like.

A concise way to state not only the desired endstate, but also the ranking of intermediate states, is through a environmental index (EI), or “ecological production function”. A environmental index is a function that allows us to aggregate apples and oranges or, in this specific case, N and P reduction. In the following examples, a combination of N and P reductions is (in some sense) “better” than another if the index assign them a higher value. It could be “better” in terms of its impact on human welfare, in terms of how it affects the conditions for biodiversity etc. – and would likely look different depending on the objective that we want to acchieve.

We will create three examples of indicies based on the linear, Leontief and Cobb-Douglas functional forms. The three functional forms imply different levels of substitutability between the individual variables (i.e. different curvature of the level sets). In that which follows, we will sometimes refer to a index with higher substitutability as more “flexible”. Throughout the discussion, we will also assume that it is reasonable to represent “euthropication reduction” with functions that are homogeneous of degree one. As long as we only want to know whether one set of N:P reduction is better than another, i.e. only view the index numbers as ordinal measures, or only are interested in the shape of the level sets, this qualification do not matter. When we talk about one level of reduction as being e.g. 4 percent bigger then another this do, of course, matter a lot. It also matters with respect to the grafs and discussions connected to them. If the first tonnes of nutrient reductions are viewed as having a much bigger effect than the last tonnes, each index would have to be modified through a apropriate monotone (rank preserving) transformation[8].

For each index, we will choose parameter values in order to rationalize the mix of N and P reductions choosen by the Northern Baltic Sea Water Agency ($\bar{N} = 3013, \bar{P} = 105$). At this point, each index will take the value 100. The environmental index will then allow us to talk about (N,P) reductions, or "environmental improvments", instead of having to treat them separately.

In figure 6, the slope of the SEK 624 million isocost curve, in the point $(\bar{N}, \bar{P})$, is 0.105. A linear environmental index that would rationalize $(\bar{N}, \bar{P})$ is thus:

$$Linear\ EI\ (P, N) = A(P + 0.105N) \qquad (12)$$

In order to accuire the value 100 in the point $(\bar{N}, \bar{P})$, we set A to $100/(\bar{P} + 0.105\bar{N})$. A Leontief index that would rationalize the same point is:

$$Leontief\ EI\ (P, N) = \min(\frac{B}{\bar{P}}P, \frac{B}{\bar{N}}N) \qquad (13)$$

This index would take the value *B* in $(\bar{N}, \bar{P})$, and we set *B* to 100. Finally, a Cobb-Douglas environmental index that would have an optimal point in $(\bar{N}, \bar{P})$ is:

$$CD\ EI = C * N^{0.75}P^{0.25} \qquad (14)$$

since $\frac{\partial CD\ EI}{\partial N} / \frac{\partial CD\ EI}{\partial P} = 0.105$ at $(\bar{N}, \bar{P})$. The value of the EI at $(\bar{N}, \bar{P})$ is $C * \bar{N}^{0.75}\bar{P}^{0.25}$, and we set C to $100/\bar{N}^{0.75}\bar{P}^{0.25}$.

With a environmental index, we are no longer limited to talk about the cost of N **or** P reductions but can, in a well defined manner, talk about the cost of N **and** P reductions ((N,

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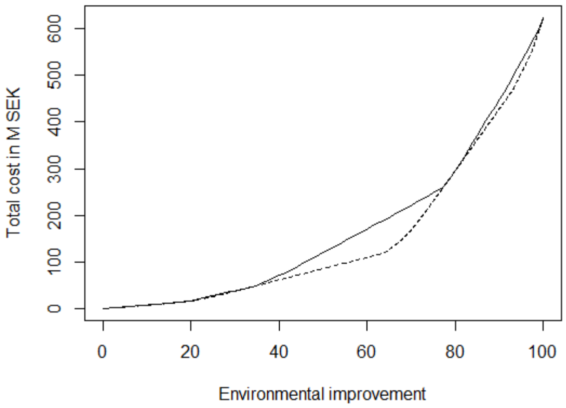
[8] E.g. $New\ index = f(Old\ index)$ where *f(.)* is a decreasing function of its argument if the first units of nutrient reduction are more important than the last.

P) reductions) or “environmental improvments”. Figure 7 below show the total cost associated with different levels of environmental quality in the linear and Leontief EI (the total cost assosiated with the Cobb Douglas index would be an intermediate case). The total cost associated with the Leontief index is found by multiplying the right hand side of equation 2 and 3 in the minimization problem with $\overline{EI}/100$, where $\overline{EI}$ is the desirable level of the index. To obtain the total cost associated with some level of the linear index, we replace equation 2 and 3 with:

$$A(\boldsymbol{Pred^T} * \boldsymbol{a} + 0.105\boldsymbol{Nred^T} * \boldsymbol{a}) \geq \overline{EI} \qquad (15)$$

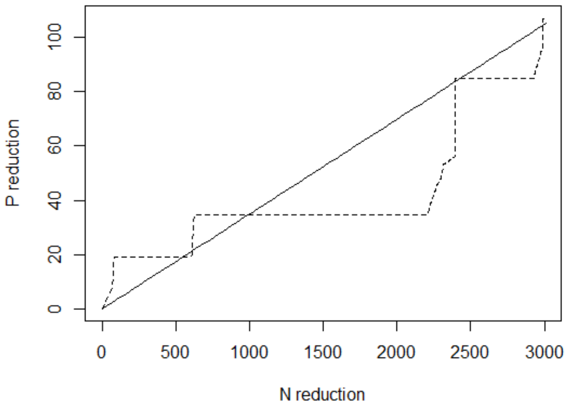
Figure 8 show what amount of N and P reductions that would be chosen in order to minimize the cost of achieving the required environmental quality.

Figure 7: TC of environmental improvement



Solid line=Leontief index, Dotted line=Linear index

Figure 8: N and P reduction in tonne



Solid line=Leontief index, Dotted line=Linear index

As the environmental quality goes towards 100, the total cost associated with each index converge towards 624 million Sek. This is by construction, i.e. both indices are supposed to rationalize the same mix of reductions at this point. It is thus more interesting to se what happens on the way there. As might have been expected, the total cost associated with the linear index is never bigger than that associated with the Leontief index. Since both the Leontief and linear (and Cobb-Douglas) environmental index are homogeneous of the first degree, i.e. takes a value X times larger if we increase each type of nutrient reduction by X times, and both take the value 100 at $(\overline{N}, \overline{P})$ - we also know that each index can achieve an index value of e.g. 50 by $(0.5\,\overline{N}, 0.5\,\overline{P})$. However, in order to acchieve a EI value of 50, the

Leontief index require at least $0.5\,\bar{N}$ and $0.5\,\bar{P}$, while the linear index imply that the same quality improvement could be achieved through for instance $(0.67\,\bar{N}, 0)$, $(0, 2\,\bar{P})$ or $(0.53\,\bar{N}, 0.4\,\bar{P})$ as well. Thus, for each level of environmental quality, the set of possible *(N,P)* reductions that would acchieve the target according to our Leontief index is a strict subset of those *(N,P)* reductions that would fullfill the linear EI´s requirement. Since the linear index allows for a greater flexibility than the Leontief index in how the goal is reached, and since the minimum cost alternative of a set of alternatives cannot be higher than that of a subset of those alternatives, the total cost associated with the linear EI has to be lower or equal to the total cost associated with the Leontief EI.

$$\{P, N | Linear\ EI\ (P,N) \geq \overline{EI}\} \supseteq \{P, N | Leontief\ EI\ (P,N) \geq \overline{EI}\}$$

$$=> Min\ Cost\ (\ Linear\ EI\ (P,N) \geq \overline{EI)}\ \leq Min\ Cost\ (Leontief\ EI\ (P,N) \geq \overline{EI}) \qquad (16)$$

Table 3 show the same thing as figure 7, i.e. the total cost assosiated with the fullfillment of either the Leontief or Linear index.

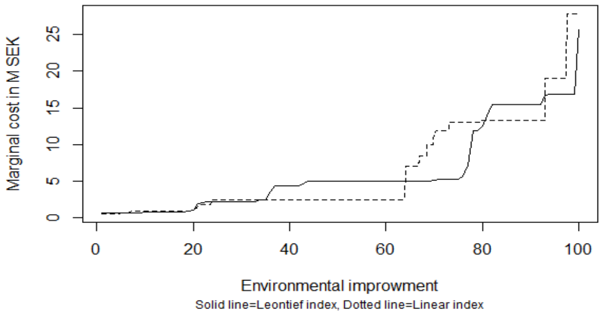
Table 3: Total cost assosiated with the fullfilment of the Linear and Leontief EI

EI level	40	50	60	90
Leontief EI, TC in M SEK	70	119	170	448
TC Linear EI, TC in M SEK	62	86	110	434
Difference in TC	8	33	60	14

Of course, this does not imply that we should use a linear environmental index instead of a Leontief. The shape of the environmental index, or the goal function, is not for the economist to decide at will. If the index is intended to show, say, the expected reduction in euthropication – the level set of the index function should describe those combination of , N and P reductions that we think could produce the same expected level of euthropication reduction. It does, however, imply that there might exist big potential gains in at least asking the question of whether it might be reasonable to acchieve a bit more of one goal at the expense of another. If it is reasonable in the specific case of P and N reductions, as some actors seem to suggest (and as we will assert in the next section), the SEPA´s suggestion to establish separate quotas and markets for N and P reductions, and the Swedish commitments in accordance with the Baltic Sea Action Plan, might lead to more expensive measures than nessecary. In the wider contex of the EU water directive, where decreased euthropication is one of many goals, and where the choosen index of water quality is very similar to what we here call a Leontief environmental index – the potential gain of asking the same basic question could be even bigger.

The environmental indicies also allow us to talk about the marginal cost of “environmental improvments”, shown for the linear (equation 12) and the leontief index (equation 13) in figure 9.

Figure 9: MC for environmental improwment



While the linear environmental index implied a lower total cost for each level of environmental improvement, the same is not true with respect to the marginal cost. If the estimated marginal benefit of environmental improvments had been, say, SEK three million, and the goal was a “socially efficient” environmental policy, the use of an Leontief environmental index would have suggested that we should acchive 35 units of environmental improvement (1055 and 37 tonnes of N and P reduction) while the linear environmental index instead would have implied 64 units of environmental improvement (2215 and 37 tonnes of N and P reduction). If the marginal benefit of environmental improvements instead had been SEK 8 million, the Leontief and linear indexies would have suggested 77 and 67 units of environmental improvement respectively.

At the suggested level of environmental improvement, i.e. a index value of 100, both the linear and Leontief index suggest a marginal cost of about SEK 27 million. A four percent less ambitious goal, i.e. a goal of 94 units of environmental improvement, would lower the marginal cost of the last unit of improvement by SEK 10 million. At a ten or 25 percent less ambitious goal, the marginal cost would be almost half or a fifth as high, respectively, as for the stated goal. If we, furthermore, would have assumed that the first units of nutrient reduction were more important than the last ones, these significantly lover marginal costs would have been even closer to the targeted environmental improvement.

We ended section four, on cost minimization, by noting that there also could be goals concerning the nutrient status of inland waters. In the appendix, we also showed how additional information on the location of the measures would allow us to set goals on every river, and even on subsets of each river. Such a formulation do, however, as already stated require the fullfillment of every single goal – no matter the cost. With a goal in terms of an environmental index, your options are no longer restricted to either completely ignoring inland water, or to including it as equally important as the goals concerning the sea. Instead, you could include the desired level of emission reductions in each river, but add that the fullfillment of these goals are of less importance – i.e. saying that in case it is too expensive to fullfill the goals in a certain river, the resourses are better spent on e.g. increased emission reductions to the sea.

Also, as already discussed, since the index tells us where we should go in the short term in addition to the desired end state, it would be easy to get continious uppdates concerning the relative value of emission reductions in different bodys of water, or the relative value of P and N reductions within a single body of water. Using, for instance, the Cobb-Douglas index (equation 14), and given that we already reduced nutrient emissions by 10 and 100 tonnes of P and N, another kg P reduction is 3.3 times more valuable than another kg N reduction. At a point where we already reduced N and P emissions by 20 and 1000 tonnes, another kg P reduction would be 16.6 times more valuable.

7: A flexible euthropication index

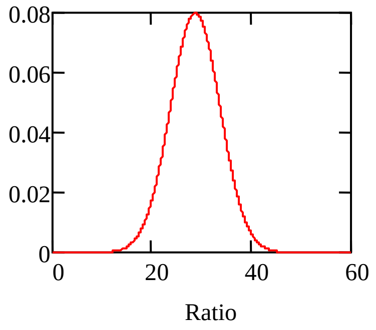
The purpose of this section is to argue that the current specification of the environmental quality goal *Zero Euthropication,* containing separate goals for P and N reductions, does not seem to be an optimal goal structure. If we only look at the present desired end state, this could be viewed as the level set of a Leontief index, giving us the minimum amount of P and N reductions that have to be acchieved without any option to compensate a failure to reach one type of nutrient reduction with increased reduction of the other. There exist other reasons, beyond eutrophication, as to why we should reduce e.g. N emissions, and it is hard to say anything about the appropriatness of theses goals, “everything considered”, without taking these issues into account. It is, however, very hard to se how a Leontief index could be a resonable index due to euthropication concerns alone.

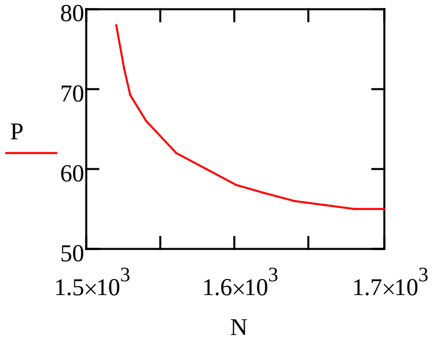
Given that our concern is with euthropication, and not N and P emissions in themselves, we want the index to reflect the way reduced emissions translates into reduced euthropication. If we knew that in order to reduce eutrophication, we need to reduce N and P emissions by a fixed ratio, and that ratio is known, a Leontief index would indeed be resonable. However, if we know that it takes a fixed ratio of N:P reductions to reduce eutrohication, but only have a estimate of that ratio, a Leontief index would no longer be reasonable unless we are extremely risk averse.

In the figure below, we instead assume that the social planer is very accepting of risk. The policy maker simply try to maximize the expected environmental quality. The social planners best guess is that the Leontif index described by equation 13 (which imply a optimal N to P reduction ratio of 28.7 N per unit of P) is correct, but have a normaly distributed ($\mathcal{N}(28.7, 5)$) belief about the true optimal ratio. While there only exist one (N,P) combination that actually cause, say, “100 units of environmental impovment”, there are, ex ante, many combinations of (N,P) that create the same expected improvement. For each $\widetilde{N}$, we want to find find a P such that

$$\overline{E\ (Leontief\ EI)} = \int_{-\infty}^{\infty} \min(ratio * \frac{B}{\overline{N}}P, \frac{B}{\overline{N}}\widetilde{N}) * Prob(ratio|Norm(28.7,5)) * dx \quad (17)$$

Where $Prob(ratio|Norm(28.7,5))$ is the normal probability density function over the ratios. $\overline{N}$ and B are the same as in equation 13 and the min function is equal to the index in equation 13 at the ratio of 28.7. The figures below show the probability distribution over the ratios and the implied index over (N,P) combinations that all give an expected environmental improvement of 50 units.





The Leontief index does not allow for any substitution in itself, and the allowed tradeoffs are not that big. However, these tradeoffs might be rational to allow even if we, with certainty, know that the environmental problem require some fixed proportion of N and P reduction.

The real relationship beetween nutrient reductions and euthropication is, however, as likely to be a function of P alone. In fact, when the SEPA put together a committee of highly qualified eutrophication scientist, there were disagreement on whether nitrogen reductions would have any effects at all on the east cost, where the Northern Baltic Sea water district is located (Boesch, 2006). If the social planner believes that euthropication is linear in the amount of "other phytoplankton", but is uncertain which nutrient factor that is the limiting one – believes in outbreaks of cyanobacteria at to low N:P ratios - and, finally, want to maximize the expected eutrophication reduction – a relevant environmental index, at least for a marginal change in the nutrient load[9], could be:

$$Expected(Euthropication\ reduction) = p_N N + (1 - p_N)7P + p_N f_C(N) \qquad (18)$$

where the first two additative terms describes the effect of the presens of "other phytoplankton" on euthropication and p_N is the probability that N is the limiting factor. The *7*, in front of *P*, is motivated by the Redfield ratio. With p_N equal to 0.5, i.e. when each nutrient is equally likely to be the limiting factor, the "other phytoplankton" part of the index above would imply the same relative price on N and P reductions as were suggested by

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[9] For a non marginal change in N or P, p_N should not be a constant, but rather a function of the new N:P ratio. I.e. as we reduce the N loading (relative to the P loading), the probability that N is the limiting factor (p_N) should increase.

the Nordic Environment Finance Corporation (NEFCO, 2008). The first part of the index is, however, followed by the functionf_C (which would be decreasing in its argument), describing the effect of cyanobacteria growth, which would be a potential problem in case of N reduction in an N-limited environment. A more general formulation, which allow for risk averseness, would be:

$$Euthropication\ EI = p_N g(N + f_C(N)) + (1 - p_N) g(7P) \qquad (19)$$

The more we prefer some euthropication reduction with certainty, rather than a chance at really big reductions, the faster the function *g(.)* should decrease with respect to its argument[10]. At the limit, with very high risk aversness (and $f_C{}' < 1$), we are essentially back at the Leontief index – but such a high risk aversness is not the norm. Thus, there are good reasons to believe that a eutrophication index, and thus policy, should allow more flexibility in the way the ultimate goal, reduced euthropication, is achieved.

8: Extension - combining centralized optimization with decentralised information.

A problem with this kind of centralized optimization is that even if we here take two effects into account (or three if we count cost), there exist many additional effects that still are missing from the model, and hence not taken into account. Even if we limit our attention to those direct and indirect effects that have a significant impact on human welfare, our analysis will still often be rather limited. The construction of wetlands, for example, might have an effect on the emissions of greenhouse gas, biodiversity and recreation, among other things. One way to proceed would be to try to include additional effects into the model, but the effects might be very different between varius geographical locations and measures. Furthermore, the effects might be hard to quantify and/or to aggregate into the goal function that is chosen for the primary problem. Another, less ambitious, way to proceed could be to simply report the measures “shadow value” (the negative of the capacity constraints shadow price), i.e. the amount we would be willing to pay in order to use another unit of the measure.

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[10] More precisely, the second derivative of the function should be large relative to the first derivative.

Table 4 show the shadow value of the measures given different assumptions about the shape of the environmental index. With respect to the linear EI, the relative value of P compared to N is a constant, and already specified by the objective function. Thus, given the linear index, we calculate the shadow values of the measures by:

$$Shadow\ value, Measure\ i = A(Pred_i + 0.105Nred_i) * LEIs - Cost_i$$

$$= effect\ of\ the\ measure * the\ value\ of\ the\ effect - cost\ of\ measure \qquad (20)$$

Where *A* is the same as in equation 12 and *LEIs* is the shadow price of the linear index, i.e. the cost assosiated with a marginal improvment of the index.

When it comes to the Leontief index, the relative value of N and P are, however, highly dependent on the already achieved reductions. If the amount of already acchieved N reduction is more than 28.7 times the already acchieved P reduction, additional N reductions are completely useless. Since the Leontief index is bound to pick a point on one of the flat sections of the isocost line, it should however be possible to adjust towards the optimal mix of N and P at a tradeoff roughly similar to the slope of the budget set. Thus, when it comes to the Leontief index, we calculate the shadow values of the measures by:

$$Shadow\ value, Measure\ i = Ns * Nred_i + Ps * Pred_i - Cost_i \qquad (21)$$

Where *Ns* and *Ps* are the shadow values of N and P from a solution to the cost minimization problem in section 4, equation 1-4, with $\overline{P}$ and $\overline{N}$ set to the values that would acchieve a improvement of the leontief EI by 100 or 50 units, depending on scenario.

Table 4: Shadow values of the measures given different assumptions about the shape of the environmental index.

DATA			Leontief=100		Leontief EI = 50		Linear EI =50	
Nr	**Measures**	**Kapacity**	**Shadow value**	**Optimal mix**	**Shadow value**	**Optimal mix**	**Shadow value**	**Optimal mix**
	P-dams, more effective							
1	I	96	340300	96	139900	96	135140	96
2	II	288	257800	288	101200	288	6370	288
3	III	96	175300	96	62440	96	-772	0
	P-dams, less effective							
4	I	64	70220	64	13810	64	-17799	0
5	II	192	37230	192	-1682	0	-20646	0
6	III	64	4235	64	-17182	0	-23503	0
7	Protective zone, more efficient	4550	6409	4550	-334	0	-2002	0
8	Protective zone, less efficient	11375	3769	11375	-1574	0	-2231	0
	Wetlands, more efficient							
9	I	380	297700	380	83500	380	20290	380
10	II	1140	50330	1140	4000	1140	-11171	0
11	III	380	-14466	0	-24300	0	-26828	0
	Wetlands, less efficient							
12	I	480	-8820	0	-22970	0	-31820	0
13	II	1440	-12120	0	-24520	0	-32105	0
14	III	480	-15420	0	-26070	0	-32391	0
	Sewage plants+ industry N							
15	I	530000	671	530000	38	530000	38	530000
16	II	1590000	633	1590000	0	832920	0	1066100
17	III	530000	363	530000	-270	0	-270	0
	Sewage plants + industry P							
18	I	9580	6450	9580	2950	9580	421	9580
19	II	28740	3500	28740	0	7780	-2528	0
20	III	9580	0	5013.5	-3500	0	-6028	0
	Individual sewers							
21	I	4000	6220	4000	-130	0	-2658	0
22	II	12000	3268	12000	-3582	0	-6111	0
23	III	4000	0	3166	-8250	0	-10778	0

In the following, we will only discuss the first column of shadow values, implied by either the goal “Leontief EI=100” or, similarely, the separate N and P goals in the Northern Baltic Sea programme of meassures. If we e.g. removed a measure of type one, “P-dams, more efficient; Class I”, we would have to find another measures to make up for the increased emissions of N and P, but would be able to avoid having to pay for that particular measure (see equation 21 above). If we made up for this loss by using the cheapest measures still available, measures of type 20 and/or 23, the cost would increase by SEK 340 thousand. The shadow value of measures in category 20 and 23 is zero, since these are the measures that are used on the margin. At the optimal mix of measures, there are about 4500 additional available measures in category 20, and the removal of one of these measures from the optimal mix could be substituted by another identical measure. Finally, the shadow value of measures 11-14 is negative, telling us that the cost would increase if we for some reason wanted to include these measures into the optimal mix.

With the shadow prices at hand, a more decentralized agency and/or other actor can get a sence of the value that a measure has in the overall strategy. If this actor know that the local implementation of a particular measure will create additional benefits and costs, and that the added net benefits will change the value of the particular measures from positive to negative or vice versa, this could be communicated back to the central agency. If a local implementation of e.g. a measure of type six would imply additional costs of more than SEK 4200, the particular measure should be excluded from the optimal mix. If, on the other hand, the implementation of a measure of type twelve would create more than SEK 8800 of extra net benefits, it should be included.

Thus, allowing for a bit of back and fourth between the central agency and local actors, the centralized optimization can easily be combined with knowledge of a more local character. The potential for such a scheme to produce reliable information is, however, dependent on the actors incentives to report the correct information.

In the SEPA´s suggested cap and trade market for nutrient reductions, efficient measures would be identified by:

1: Allow actors without emission restrictions to leave offers concerning measures and costs.

2: Allow actors affected by emission reductions to choose whether they want to implement measures themselves or buy credits from others.

There is, however, a cost associated with the formulation of an offer and some potential actors might not even notice the new opportunity. A crude initial analysis, based on the limited avaliable information about potential measures, like the one conducted in this paper, could be done before the call for offers. The shadow prices concerning N and P reductions could give actors without emission restrictions a rough estimate of wheter they should bother to compete on the supply side at all. Likewise, the shadow values of different measures could give the agency, or the actors affected by emission restrictions, an idea of which groups that could be targeted with information concerning the new avalible opportunitie.

Another way the results could be used would be to take the shadow prices for N and P reuduction and, where apropriate, use these as the levels of taxation on N and P emissions. This could probably be done with respect to sewage plants and industry. Likwise, the shadow prices could be used to determine subsidies to actors who create measures for N and P retention. This type of policy could target the creation of wetlands, phosphorus dams, protective zones and this far unidentified measures (as long as these actors would face a subsidy, rather than a tax, they should have incentive to step forward as long as the subsidy is larger than their cost). Finally, any slack between the effect of the already mentioned policies and the goal could be targeted by more direct command and control regulation, aimed at e.g. individual sewers.

9. Discussion

In order to fulfill commitments made in the Northern Baltic Sea Action Plan, and the European Union’s Water Framework Directive, Sweden will have to implement major actions against eutrophication in the upcoming years. In order to do that, regional Water agencies have identified, and quantified, potential measures.

The various goals concerning eutrophication are usually expressed as separate goals for nitrogen and phosphorus emissions. The measures that are suggested to deal with the emissions do, however, often have an effect on both types of emissions at the same time. Thus, the goals cannot be treated separately, but have to be analyzed simultaneously. We show how the cost minimizing set of measures can be found, and we note that the measures suggested in the Northern Baltic Sea Programme of Measures are inefficient, in the sense that the same emission reductions could be achieved SEK 45-35 million (5-7 million USD) cheaper. We also show that focusing on one goal at the time, starting with N reductions, would be more expensive than taking both goals into account at the same time. The data is, however, rather coarse and a final analysis would likely have to include the location of the measure in order to avoid hotspots and/or take upstream retention into account.

In the next few sections, we turn to look at the goal(s) itself. In order to get a good overview of the policy space, i.e. the available options, we start by plotting budget sets – i.e. the different amounts of N and P reduction that is possible to achieve at different levels of total cost. While Sweden already have goals concerning N and P emissions, as well as many other environmental concerns, they should not be interpreted to literally – and while international agreements may make it hard to formally change the goals, the actual, policy backed, goals are under constant reevaluation. A casual look at the plotted options makes it clear that the relative cost between N and P reductions vary a lot depending on the chosen ratio of N to P reductions, and that the absolute cost of either N or P reductions vary a lot depending on the absolute level of N and P reductions. This, in turn, implies that relatively small changes in the targeted N:P ratio, or absolute N:P level, might result in large cost reductions – and one might hope that the actors who determined the goals looked at the complete picture before they specified it.

Two hypothetical eutrophication indices, one linear (i.e. rather flexible) and the other a Leontief function (i.e. no flexibility) both imply that the marginal cost of eutrophication reduction increase by over one third during the last 4% of the goal fulfillment. At a 10% less ambitious goal, the last units of eutrophication reduction would only cost about half as much and at a 25% less ambitious goal, a fifth as much, as the last units of the suggested goal. Thus, even if the total benefits of the goal might be deemed superior to the total cost, it might be reasonable to consider whether the last units of the goal fulfillment are superior to its marginal cost. Given that the last units of proposed eutrophication reduction are achieved at a marginal cost of about 40 times that of the first units, we either have had an extremely inefficient policy, are about to introduce an extremely inefficient policy, or are faced by a combination of the two extremes (i.e. maybe we only have avoided to make investment with 20 times higher benefit than cost, but now are about to make investments where the cost is twice as large as the benefit).

To set the goal(s) as a level of an environmental index dominates the communication of the goal(s) as desirable end states. The index tells you about the desirable end state, but also gives you information about the relative desirability of states short of the goal(s). The improvements towards a goal might lose momentum, and be left of the agenda for many years. It might thus be important to get the right thing done, even in the short term. In the construction of the index, you are also forced to at least consider whether some tradeoffs could be accepted. In the case with eutrophication, which depends on both the analyzed nutrients, an environmental index, or eutrophication index, would allow us to talk about the total and marginal cost of eutrophication reduction. We also suggest a particular index for marginal changes in euthropication reduction, i.e.:

$$Euthropication\ EI = p_N g\big(N + f_C(N)\big) + (1 - p_N) g(7P)$$

Where p_N is the probability that N is the constraint on biological growth of "other phytoplankton". If we assume that $f_C()$, the weight we put on cyanobacteria, is linear with respect to the amount of cyanobacteria and that the decision maker is risk neutral (making the *g()* function, represent the social planers risk preferences, superfluous), the index is linear – i.e. allows for a lot of flexibility with respect to how we achieve the goal. We also show that even if we, with certainty, know that N and P in fact has to be reduced in fixed proportions – but we are unsure what those proportions are – there is still a reason to allow for some flexibility in how the aggregate eutrophication goal is reached.

Finally, as stated many times already, the present data is hardly extensive enough, or detailed enough, to settle any questions. This does not mean that it is useless. Unless it is biased in some unsuspected way, it can still give a feel of the available options. As argued in the last section, it might also be possible to combine a centralized optimization like this one with more decentralized information. It could, for example, give a first rough approximation of which actors that should bother to take notice in case the cap and trade scheme suggested by the SEPA ever is implemented.

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Appendix A

If we were to take loadings of P and N in inland waters, as well as retention, into account, the cost minimizing set of actions could still be found in much the same way as in the cost minimization problem in section 3. If we assume that there exist n rivers, divide each river into three parts, and assume that each part of the river, as well as the sea, has its own goal concerning emission reductions – the cost minimization problem could be solved by:

$$Min\, f(\boldsymbol{a}) = \boldsymbol{Cost^T} * \boldsymbol{a} \tag{A.1}$$

$$\boldsymbol{a} = \boldsymbol{a_{SEA}} + \textstyle\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \sum_{\boldsymbol{j=1}}^{\boldsymbol{3}} \boldsymbol{a_{i,j}} \tag{A.2}$$

s.t.

$$\boldsymbol{Pred^T} * \boldsymbol{a_{i,1}} \geq \overline{P_{i,1}} \qquad \textit{for all i} \tag{A.3}$$

$$\widetilde{Pred_{i,1}} = \boldsymbol{Pred^T} * \boldsymbol{a_{i,1}} \qquad \textit{for all i} \tag{A.4}$$

$$\boldsymbol{Pred^T} * \boldsymbol{a_{i,j}} + (1 - Pretention_{i,j-1})\widetilde{Pred_{i,j-1}} \geq \overline{P_{i,j}} \qquad \textit{for j=2,3 and all i} \tag{A.5}$$

$$\widetilde{Pred_{i,j}} = \boldsymbol{Pred^T} * \boldsymbol{a_{i,j}} + (1 - Pretention_{i,j-1})\widetilde{Pred_{i,j-1}} \qquad \textit{for j=2,3 and all i} \tag{A.6}$$

$$\boldsymbol{Nred^T} * \boldsymbol{a_{i,1}} \geq \overline{N_{i,1}} \qquad \textit{for all I} \tag{A.7}$$

$$\widetilde{Nred_{i,1}} = \boldsymbol{Nred^T} * \boldsymbol{a_{1,j}} \qquad \textit{for all I} \tag{A.8}$$

$$\boldsymbol{Nred^T} * \boldsymbol{a_{i,j}} + (1 - Nretention_{i,j-1})\widetilde{Nred_{i,j-1}} \geq \overline{P_{i,j}} \qquad \textit{for j=2,3 and all i} \tag{A.9}$$

$$\widetilde{Nred_{i,j}} = \boldsymbol{Nred^T} * \boldsymbol{a_{i,j}} + (1 - Nretention_{i,j-1})\widetilde{Nred_{i,j-1}} \qquad \textit{for j=2,3 and all i} \tag{A.10}$$

$$\boldsymbol{0} \leq \boldsymbol{a_{i,j}} \leq \boldsymbol{MaxCap_{i,j}} \qquad \textit{for all i and j} \tag{A.11}$$

$$\boldsymbol{Pred^T} * \boldsymbol{a_{SEA}} + \textstyle\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}}(1 - Pretention_{i,3})\widetilde{Pred_{i,3}} \geq \overline{P_{sea}} \tag{A.12}$$

$$\boldsymbol{Nred^T} * \boldsymbol{a_{SEA}} + \textstyle\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}}(1 - Nretention_{i,3})\widetilde{Nred_{i,3}} \geq \overline{N_{sea}} \tag{A.13}$$

$$\boldsymbol{0} \leq \boldsymbol{a_{SEA}} \leq \boldsymbol{MaxCap_{SEA}} \tag{A.14}$$

Where the vector of measures, **a**, and the maximum number of available measures, **MaxCap** (in equation 11, part 3 of the paper), would have to be disaggregated into actions available in each specific location (with $\boldsymbol{MaxCap_{i,j}}$ referring to actions available in river i, part *j*). $\overline{P_{i,j}}$ and $\overline{N_{i,j}}$ is the P and N reductions required, and $\widetilde{Pred_{i,j}}$and $\widetilde{Nred_{i,j}}$ is the P and N reductions achieved, in river i, part j. As before, the vectors $\boldsymbol{Pred}$ and $\boldsymbol{Nred}$ describe the different measures effect on the direct emissions. It is also assumed that the first part of the river is furthest upstream. If the natural rate of P retention in the first part of river x is, say, 10% (i.e. $Pretention_{x,1} = 0.1$), the decrease in P loading in part 2, due to actions taken in part 1, is 90% of their effect on the loading in part 1. If we disregard the loadings in inland waters, all $\overline{P_{\iota,\jmath}}$ and $\overline{N_{\iota,\jmath}}$ would be set to zero, and the equations containing them could be dropped from the analysis.

In a final model, the number of sections that each river is divided into could vary, and some section could signify a lake rather than a part of a river. If river x and y merge before they reach the sea, this would also have to be taken into account. If the rivers merge after, say, part 2 in river y and part 1 in river x, we could remove the downstream parts of river x from the model and modify part 3 of river y. Equation A.9 and A.10 concerning N reductions in river y, part 3, would have to be replaced by:

$$\boldsymbol{Nred}^{\boldsymbol{T}} * \boldsymbol{a}_{\boldsymbol{y,3}} + (1 - Nretention_{y,2})Nred_{y,2} + (1 - \widetilde{Nretention}_{x,1})\widetilde{Nred}_{x,1} \geq \overline{P_{y,3}}$$

$$\widetilde{Nred}_{y,3} = \boldsymbol{Nred}^{\boldsymbol{T}} * \boldsymbol{a}_{\boldsymbol{y,3}} + (1 - Nretention_{y,2})\widetilde{Nred_{y,2}} + (1 - Nretention_{x,1})\widetilde{Nred}_{x,1}$$

Finally, the equations concerning P reduction would have to be modified in the same way.