Nutrient management for coastal zones: a case study of the nitrogen load to the Stockholm Archipelago

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Abstract This study investigates cost-effective solutions of decreasing the nutrient load to a coastal area, using a drainage basin approach. The study is applied to the Stockholm Archipelago, a coastal area of the Baltic Sea suffering from eutrophication caused by the load of nutrients entering the area. Nitrogen is the nutrient of concern in this study since it is the limiting nutrient of the Archipelago. The main sources of nitrogen are wastewater plants, agriculture, and atmospheric depositions. The final impact of a deposition depends on the buffering capabilities it is subject to on its trajectory from the source to the recipient. This is the reason for using a recipient oriented approach, in which the focus is to reduce the final impact of a deposition. The model integrates data over hydrology, land cover, land use, and economy in order to find the optimal allocation of measures. Results indicate that in order to achieve cost effectiveness, the major part of nitrogen load reduction to the Archipelago should be done at the wastewater plants and by constructing wetlands. The minimum annual cost of reaching a 50% reduction of the load to the Archipelago was estimated to around 191 million Swedish crowns (around $ 19 million).

Keywords Coastal water pollution; cost effectiveness; watershed management; wetlands

Problem Eutrophication, i.e. an increased supply of nutrients stimulating the growth of plants, is one of the major threats to the environmental state of the Baltic Sea. It causes reduction in the cod population, toxic blue green algae and dead sea bottoms. This eutrophication is caused by the deposition of nutrients into the sea from surrounding countries. The amount of nutrients entering the sea must be reduced if some of the benefits derived from the Baltic Sea are to be preserved. The Stockholm Archipelago is a coastal zone of the Baltic Sea suffering from this eutrophication. The major part of the nutrients load to the Archipelago comes from deposits within its drainage basin. It is the nitrogen that is the limiting nutrient of the Archipelago and therefore the one considered in this study. The lake of Mälaren within this basin is Sweden’s third largest lake, and is connected to the Stockholm Archipelago by Norrström. A large fraction of the nutrient load into this lake is therefore eventually discharged into the Archipelago.

This study approaches the problem by looking at a main drainage basin region consisting of several sub-drainage basins. The different characteristics of these basins influence the allocation of abatement measures. A 50 percent reduction in the load of nutrients has been targeted and is based on a ministerial agreement between the countries surrounding the Baltic Sea (HELCOM declaration, 1988). There are several measures available for reducing the nutrient load. The decision problem is to minimize the total cost of these measures for a given target of reduction. This paper will emphasize the importance of using a recipient approach in which the objective is to consider a measure’s impact on the final load. It is vital to include the buffering capabilities the deposition is subject to on its trajectory from the source to the recipient, since it will influence the final impact. Sufficient data over the nutrient pathways is therefore of great importance. The aim of this study is to take these factors into consideration in finding the cost-effective way of reducing the nutrient load to the Archipelago.
The paper is structured as follows. First the model used in the cost-efficient allocation of measures is explained. This model will thereafter be applied on the drainage basin of the Archipelago, which is described in the empirical section. In this section the results from the optimization will also be presented. Finally, conclusions are drawn from our results together with a discussion.

Method
Depositions of nitrogen within one of the \(i = 1, \ldots, n\) different drainage areas, might either be discharged directly into a water body, \(D^{id}\), or indirectly, \(D^{idL}\), meaning it is deposited over land. Examples of sources causing land deposition are agriculture, forest management and livestock production. Plants utilize some part of the deposited nitrogen, while the remaining part will leach away from the root zone. The amount of leaching nitrogen from farmed land prior to land use measures is a function of crop management, water run-off, soil type and meteorological conditions (Johnsson and Hoffman, 1997).

Leaching nitrogen from land deposition can thereafter reach a recipient in one or several of the following ways of water transportation:
- groundwater flow discharging into the catchment stream network, which in turn leads the nitrogen to the recipient;
- direct groundwater flow into the recipient;
- surface water flow to streams or directly into the recipient.

During water transportation, the nitrogen is subject to plant assimilation, sedimentation and denitrification, which reduces the final load. The proportion of leached nitrogen that, due to these factors, does not reach a body of water is referred to as retention.

Nitrogen is also discharged directly into the water body without being subject to the same reductions as land deposited nitrogen. These discharges are referred to as direct deposits. Direct deposits are either discharged directly into Lake Mälaren or into the Archipelago. Examples of direct deposition are municipal and industrial point discharges as well as the atmospheric deposition on the water surface.

The nitrogen discharged into Lake Mälaren from indirect land depictions and direct deposions is subject to the nutrient sink capacity of the lake before reaching the Archipelago. The Lake is divided into 5 different lake basins, all with their respective nutrient sink capacity. The total load of nitrogen entering a lake basin of Mälaren, \(D^b\), is determined by the discharge directly into the lake, \(\sum_i D^{idb}\) as well as the discharge from indirect sources within its drainage basin, \(\sum_i N^{idLb}\) plus the amount it receives from other lake basins, \(\sum_c a^{cb} D^c\). That is

\[
D^b = \sum_i (D^{idb} + N^{idLb}) + \sum_c a^{cb} D^c, \tag{1}
\]

where \(a^{cb}\) denotes the fraction of the nitrogen load from other lake basins entering this specific basin.

The nitrogen discharges from a certain drainage basin reaching the archipelago, \(A^{Ni}\), is given by the following equation

\[
A^{Ni} = \sum_b a^{bA} D^b (D^{id} + N^{idL}) \tag{2}
\]

where \(0 \leq a^{bA} \leq 1\) denotes the nutrient sink capacity of Lake Mälaren. This fraction takes the value 1 if the drainage basin in question is adjacent to the Archipelago.

The total load of nitrogen from the drainage basin region that reaches the Archipelago, \(A^N\), is the sum of all direct and indirect loads from adjacent drainage basins plus the amount that flows in from Lake Mälaren by Norrström.
\[ A^N = \sum_b a^{Abr} D^{b} + \sum_i (D^{idA} + N^{idLA}) \]

where \( 0 \leq a^{Abr} \leq 1 \) denotes the fraction of the nutrient load to Lake Mälaren that reaches the Archipelago, and is determined by the lake’s nitrogen sink capacity.

In summary the fraction of deposited nitrogen reaching the recipient is determined by leakage of deposited nutrients, the reduction of nutrients during the water transportation, which is called retention, and the nutrient sink capacity of concerned lake basins. The latter of these only affects nitrogen deposited directly into Lake Mälaren.

Several different abatement measures, \( M^k \), where \( k = rdl, rd, l, s \), can be applied to reach a given target of reduction. They are all aimed at reducing the nitrogen load, \( A^N \), to the recipient. The measures can be divided into the following three sub-groups:

- reducing the deposition of nitrogen, either from fertilizers, \( M^{rdL} \), or from wastewater plants, \( M^{rd} \);
- reducing the leakage, \( M^l \), of nitrogen from land deposition, by cultivating catch crops;
- increasing retention, \( M^s \), by constructing wetlands.

Each measure differs with regard to reduction capacity, abatement costs, and final impact on the load, and group targeted. Each measure is restricted by an upper limit, \( M^k \), due to different capacity characteristics. It might, for example, not be technologically possible to reduce the load from wastewater treatment plants by more than 80 percent, with the available technology. Land available for wetland creation and the maximal possible reduction of leakage by catch crops are other examples of restrictions on the capacity.

The problem of the planner, as mentioned above, is to minimize total abatement costs for a given abatement target. Abatement costs are a function of the measure in question, \( C = C(M) \), i.e. the cost for that specific measure to abate one unit of nitrogen. Abatement costs are determined by the society’s opportunity cost of the measure taken and do not necessarily equal the cost carried by the regulated part. Examples of abatement costs are investments in cleaning technology; the value of lost production due to a reduction in the use of fertilizers, and opportunity cost of land set aside for wetland construction. The abatement cost function is assumed to be convex and increasing, implying that marginal cost of abatement increases at an increasing rate. That is \( C'_M > 0 \), and \( C''_M > 0 \). In other words, it becomes successively more expensive to apply a measure.

The choice of environmental target has vital implications for the result due to its effect on costs and optimal allocation of measures. The target is expressed as a maximum load of nitrogen to the Archipelago, \( A^{N*} \), that cannot be exceeded by the load from all its drainage basins. That is

\[ \sum_i A^{Ni} \leq A^{N*} \]  

(3)

We now have all equations and restrictions required in setting up the planner’s problem, which is to minimize the costs of a 50 percent reduction of the load to the Archipelago given the equations and restrictions described above. That is

\[
\begin{align*}
\text{Min} & \quad \sum \left[ \sum_{rd} C^{rdL} \left( M^{rdL} \right) + \sum_i C^{id} \left( M^{id} \right) + \sum_s C^{is} \left( M^{is} \right) + \sum_{rd} C^{rd} \left( M^{rd} \right) \right] \\
\text{s.t.} & \quad (1) - (3).
\end{align*}
\]

Solving this problem generates the following first order condition for an optimal allocation of measures, where subindexes denote partial derivatives,

\[
\frac{C^{id}_{M^{id}} + \mu^{id}_{M^{id}}}{\psi^{M^{id}}} \geq \delta
\]
where \(0 \leq \Psi^{M_{ik}} \leq 1\) indicates the impact on the final load to the Archipelago of that specific measure, as well as its impact on the efficiency of other abatement measures. The nominator on the left-hand side of the equation gives the marginal cost of a measure at the source, \(C^{M_{ik}}\), plus the cost imposed if that specific measure’s capacity of reducing the nitrogen load is binding, \(\mu^{ik}\). The left-hand side of the equation, thereby, stands for the cost of a specific measure in reducing the final load to the Archipelago by one unit.

The term on the right hand side, \(\delta\), is interpreted as the change in total costs of reducing the nitrogen load by one unit at the recipient, or in other words, the shadow price of a load restriction at the recipient. If a measure is to be implemented it should be so until the left-hand side of the equation is equal to the right-hand side. That is, as long as a measure’s marginal cost of reducing the final load by one unit is less than the marginal cost of load reduction at the recipient. It can be seen that if the impact on the recipient of a measure is low the marginal cost of reduction of that measure will be high.

For abatement measures taken at wastewater treatment plants in drainage basins adjacent to the Archipelago the impact of a marginal increase in this measure on the recipient will be unity, that is \(\Psi^{ik} = 1\) in the first order condition above. This means that reducing nitrogen by 1 ton at the wastewater treatment plant also reduces the load to the Archipelago by 1 ton.

In summary, the first order condition for an optimal allocation of abatement measures considers final impact on the recipient, the capacity limit and costs of measures, and finally how the use of one measure affects the efficiency of another. The availability of data and information concerning these factors are therefore of vital importance when applying the model.

**Application to the Stockholm Archipelago**

The drainage basin of the Mälar region covers an area of about 26,500 square kilometres of which Lake Mälaren stands for a little more than 4 percent. Sixteen major streams drain this basin, of which 5 flow directly to the Archipelago and 11 are contributors to Lake Mälaren (Statistical data for drainage areas, 1994). The region remained under water for a long while after the last ice age and is still rising. Glacial and post-glacial processes therefore dominate its geomorphologic features. The thick layer of clay rich soil (mainly post-glacial and glacial clay) which is to be found in valleys and other low parts of the region is a typical example of such a feature. These areas of clay rich soil makes a good base for agricultural production, and it is there most of the farmed land is found.

Forest dominates the land covering 51 percent of the area. Farmed land accounts for 17 and pasture for 2 percent, indicating that deposition of fertilizers is of greater concern than livestock holding as a nitrogen source. There reside about 2.5 million individuals in the region (Statistical data for drainage areas, 1994); 90 percent of these live in cities of which the major part are in the great Stockholm region.

The nitrogen sink capacity of Lake Mälaren has a great impact on the allocation of measures. Mälaren is divided into 5 different lake basins, with their respective catchment areas (A to E), separated by more or less significant lake bottom thresholds (Persson *et al.*, 1989). These basins differ with regard to depth, volume and area. These differences are important factors in determining the residence time of water and the nitrogen sink capacity of each basin. The exchange of nitrogen between the lake basins is in one direction i.e. there is only a flow from upstream to downstream basins and no flow in the opposite direction. The catchment area for nitrogen depositions from the adjacent drainage basins of the Archipelago is referred to as catchment area F.

Data concerning depositions, land-use, retention and other vital characteristics were used in order to estimate the nitrogen discharges from each catchment area. Most of these
data were available on a smaller drainage basin level then the one described above. Catchment areas A to F can therefore be divided into 33 smaller drainage basins in the application of the model. The estimates and results are for the sake of simplicity presented on the catchment area level.

The load of nitrogen into the Archipelago is, as mentioned, the main cause of eutrophication. The major part of this load comes from the drainage basin of the Mälar region. Sources of nitrogen deposition are forests, livestock holdings, agriculture, wastewater treatment plants, and air emissions from traffic and stationary combustion sources. The major part of depositions in this region comes from wastewater treatment plants and fertilizers, which can be seen in Table 1 below. The total amount of nitrogen (N) being discharged into the six basins amounts to 12,053 tons per year.

Due to the nutrient sink capacity of Lake Mälaren only 58 percent of the total discharge of 12,053 tons reaches the Archipelago. The final amount from each drainage basin that reaches the Archipelago is displayed in Table 2 below. This table emphasizes the great impact on the final load of drainage basin F, as well as the little impact of the distant drainage basin A. The further away from the Archipelago the deposition takes place the smaller the impact of it will be.

The final load of nitrogen into the coastal zone of the Stockholm Archipelago is 6,937 tons per year. Approximately half of this amount comes from its adjacent catchment area while the rest flows in from Lake Mälaren. Since this study concentrates on the eutrophication of the Archipelago the objective will be to reduce this final load by 50 percent, ignoring the impact of nitrogen on Lake Mälaren as well as the Baltic Sea.

**Results**

Using the information from the previous section allows for solving the optimization problem of minimizing the costs for a reduction of the nitrogen load to the Archipelago. The results were obtained by using Gams modeling program. A 50 percent reduction of the

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**Table 1** Nitrogen discharges into the basins of the Mälar region, tons of N/year (Statistical data for drainage areas, 1994; Arheimer et al., 1997; Widell, 2000)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Land deposition</th>
<th>Direct</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Forest land</td>
<td>Fertilizers</td>
</tr>
<tr>
<td>A</td>
<td>468</td>
<td>413</td>
<td>499</td>
</tr>
<tr>
<td>B</td>
<td>209</td>
<td>689</td>
<td>1343</td>
</tr>
<tr>
<td>C</td>
<td>83</td>
<td>343</td>
<td>246</td>
</tr>
<tr>
<td>D</td>
<td>186</td>
<td>693</td>
<td>568</td>
</tr>
<tr>
<td>E</td>
<td>26</td>
<td>121</td>
<td>38</td>
</tr>
<tr>
<td>F</td>
<td>302</td>
<td>583</td>
<td>2449</td>
</tr>
<tr>
<td>Total</td>
<td>1,274</td>
<td>2,842</td>
<td>5,143</td>
</tr>
</tbody>
</table>

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**Table 2** Nitrogen loads from different drainage basins to the Stockholm Archipelago, tons of N/year (Persson et al., 1989)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Land deposition</th>
<th>Direct deposition</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>282</td>
<td>429</td>
<td>711</td>
</tr>
<tr>
<td>B</td>
<td>314</td>
<td>818</td>
<td>1,132</td>
</tr>
<tr>
<td>C</td>
<td>187</td>
<td>367</td>
<td>554</td>
</tr>
<tr>
<td>D</td>
<td>466</td>
<td>361</td>
<td>827</td>
</tr>
<tr>
<td>E</td>
<td>113</td>
<td>102</td>
<td>215</td>
</tr>
<tr>
<td>F</td>
<td>885</td>
<td>2,613</td>
<td>3,498</td>
</tr>
<tr>
<td>Total</td>
<td>2,247</td>
<td>4,690</td>
<td>6,937</td>
</tr>
</tbody>
</table>
The nitrogen load to the Archipelago could be achieved at a cost of 191 millions Swedish crowns (SEK) per year. The allocation of this cost between the regions and measures is illustrated in Table 3 below. The table presents the costs of abatement for the different measures as well as for the different regions.

Reduction at wastewater treatment plants will stand for 67 percent of the total costs, which is not surprising. Foregone profits caused by fertilizer reduction accounts for 30 percent and wetland construction for 3 percent of total costs, while cultivation of catch crops stands for less than 1 percent.

Turning from the allocation of costs to the allocation of measures, it is not surprising that it follows the same pattern. Measures will reduce the total amount of discharged nitrogen by 5,500 tons generating a load reduction to the Archipelago of 3,468 tons.

Reducing the discharge from the wastewater plants stands for 75 percent of total nitrogen discharge reduction and 82 percent of the reduced load to the Archipelago, while reduced usage of fertilizer accounts for 19 percent of total reduction and 14 percent of load reduction. Wetlands will stand for 6 percent of the reduction and 4 percent of the load reduction. Catch crops will stand for less than 1 percent of the reduction and will only be cultivated in region F at this level of reduction.

It is logical that wastewater plants stand for the major part of reduction considering that their impact is not subject to retention, and therefore are relatively inexpensive, as well as the fact that they stand for the largest part of the discharges. All wastewater plants should reduce their discharge all the way up to the capacity limit; i.e. all plants should reduce their nitrogen discharges by 80 percent. Wetlands will also reduce up to their full capacity. Reduction of fertilizers should be done in most sub-drainage basins, but to a greater extent by the ones with a larger impact on the Archipelago, and in the basins in which wetlands cannot be used as a measure. Catch crops should only be cultivated in one of the sub-drainage basins of region F.

This distribution of reduction between the regions is explained by their differences concerning deposition, impact, and capacity limits of measures. The large amount of discharges from wastewater plants in region F as well as the fact that measures in the other regions are subject to the nutrient sink capacity of Lake Mälaren, explains why this region will make the most effort in reducing its nitrogen.

**Conclusions**

The importance of taking the characteristics of different drainage basins into consideration when searching for a way to reduce the nitrogen load is one of the main conclusions in this study. The sources should be managed with regard to their impact and not their deposition, if a cost efficient reduction is to be achieved. Treating all depositions equally without regarding their actual impact when determining a reduction policy would lead to great losses of efficiency. That is, to reach the target would in such cases be more expensive, or the

### Table 3 Allocation of nitrogen reduction costs, thousands SEK/year (Byström, 1998; Gren et al., 1995; Gren et al., 1997a, b; Håkansson, 1989)

<table>
<thead>
<tr>
<th>Region</th>
<th>Wastewater</th>
<th>Costs of N-reduction to the Archipelago</th>
<th>Total (region)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12,375</td>
<td>672</td>
<td>1,060</td>
</tr>
<tr>
<td>B</td>
<td>33,306</td>
<td>3,300</td>
<td>2,238</td>
</tr>
<tr>
<td>C</td>
<td>6,101</td>
<td>6,368</td>
<td>64</td>
</tr>
<tr>
<td>D</td>
<td>14,086</td>
<td>18,823</td>
<td>1,263</td>
</tr>
<tr>
<td>E</td>
<td>942</td>
<td>5,493</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>60,735</td>
<td>22,546</td>
<td>544</td>
</tr>
<tr>
<td>Total (measure)</td>
<td>127,545</td>
<td>57,202</td>
<td>5,169</td>
</tr>
</tbody>
</table>
other way around, for the same cost a higher target of reduction could be obtained by taking a recipient approach.

The degree of uncertainty, with regard to the parameters used, has to be emphasized. The actual values of estimated results should therefore be considered with caution. Conclusions can however be taken by observing the relation between these values. That is, the exact amount of measures to be taken in order to reach the goal should be used with caution, while the allocation of such measures can be regarded with less caution.

Assumptions made concerning the characteristics of abatement measures can also be questioned with regard to the robustness of the results. These assumptions have been unavoidable due to data limitations, time- and scale constraints and limitations of the model used.

To manage water-transported pollution from a drainage basin perspective instead of a political border perspective would be preferable in order to achieve the allocation of measures suggested in this study. The success of such management will depend on the availability of data and reliable models of pollutant transportation. Any improvements in the understanding of pollutant transportation will increase the benefits generated by the approach described above. The need for further research in that area is therefore of great importance.

References


