SOILS2SEA DELIVERABLE NO. 3.5

BONUS
SCIENCE FOR A BETTER FUTURE OF THE BALTIC SEA REGION

Gains from differentiated regulation of nitrate in groundwater dominated Danish catchments

SOILS2SEA

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

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Gains from differentiated regulation of nitrate in groundwater dominated Danish catchments

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SOILS2SEA

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

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1. Background and objectives

The Baltic Sea Action Plan and the EU Water Framework Directive both require substantial additional reductions of nutrient loads (N and P) to the marine environment. The BONUS SOILS2SEA project conducts research on a widely applicable concept for spatially differentiated regulation, exploiting the fact that the removal and retention of nutrients by biogeochemical processes or sedimentation in groundwater and surface water shows large spatial variations. In spatially differentiated regulation, mitigation measures aiming at reducing nutrient loads, are targeted towards areas, where the local removal is low, which makes spatially differentiated regulation more cost-effective than the traditional uniform regulation.

The present deliverable describes assessments of the potential and limitations for decreasing N-loads to the sea by use of spatially differentiated strategies, where mitigation measures in terms of relocation of crops are chosen, so that the natural reduction of nitrate in the groundwater zone is exploited as much as possible.

The loss of nitrogen from agriculture in groundwater dominated catchments occurs mainly as leaching of nitrate from the root zone, which is then transported to surface waters via groundwater or drain systems. Along the flow path from the source to the catchment outlet nitrate can be naturally transformed to N_2 by nitrate reduction, which is a microbial process occurring under anoxic conditions and in the presence of an electron donor. Nitrate reduction (N-reduction) occurs in soils, groundwater and surface waters. In Denmark the N-reduction in groundwater is high due to a groundwater dominated hydrology and a shallow depth to the redox interface, which delineates the transition from oxic to anoxic conditions in the groundwater zone. Thus, in many Danish catchments more than 50% of N-leaching from the root zone is reduced in groundwater (Højbjerg et al., 2015). However; due to geological heterogeneity the amount of N-reduction in groundwater vary greatly in space, not only between catchments, but also at local scale within a catchment (Hansen et al., 2014b). Hence, both areas with high and low groundwater N-reduction typically exist within a catchment.

The potential gain from spatially differentiated regulation lies in exploiting the spatial variabilities in N-reduction within catchments (Jacobsen and Hansen, 2016). A key tool in this respect is a map showing how much of the N-leaching from the root zone is reduced on its flow path between the root zone and the sea. These N-reduction maps exist with different spatial resolution, e.g. in Denmark ranging from 1 ha for a small catchment (Hansen et al., 2014a) to 15 km^2 catchments for the entire country (Højberg al., 2015; Højberg et al., 2017). As the spatial variation in N-reduction occurs at 1 ha (or below), maps with coarse resolution (e.g. 15 km^2) will be much more smooth and a considerable part of the potential gain will therefore not be exploitable, if the regulation is based on coarse resolution maps. The fine resolution N-reduction maps are, however, associated with considerable uncertainty (Hansen et al., 2014b), which in practise will decrease the potential benefits of a spatially differentiated regulation. Other factors that will decrease the gain are that some crops cannot be relocated from one soil type to another and that individual farmers can only relocate within their own fields. As some farmers are dependent on having a certain variation of crops e.g. to ensure fodder for livestock, this will in practice constrain the gain.

The objective of the present deliverable report is to describe analyses that quantify the gains in spatially targeting measures for N in Denmark and to assess to which extent uncertainty on the hydrogeological conditions and constraints caused by agricultural management practices reduce these gains.

2. The concept of spatially differentiated measures

Nitrate transport and reduction in a rural landscape are illustrated in Figure 1. Some of the excess nitrate leaching from the root zone is transported via overland flow or surface-near flow paths, including drain pipes, while the remaining nitrate flows deeper into the groundwater system. In the upper, oxic part of the groundwater zone nitrate is transported as a conservative solute, while it, when transported into the reduced zone, will be biogeochemically reduced. Nitrate reduction in groundwater depends on the flow paths and the depths of the redox interface separating the oxic and anoxic/reduced zones (Postma et al., 1991; Hansen et al., 2014a). After leaving the groundwater zone, nitrate is subject to geochemical reduction in the hyporheic zone along the river and in sediments of lakes and rivers (Boano et al., 2014).

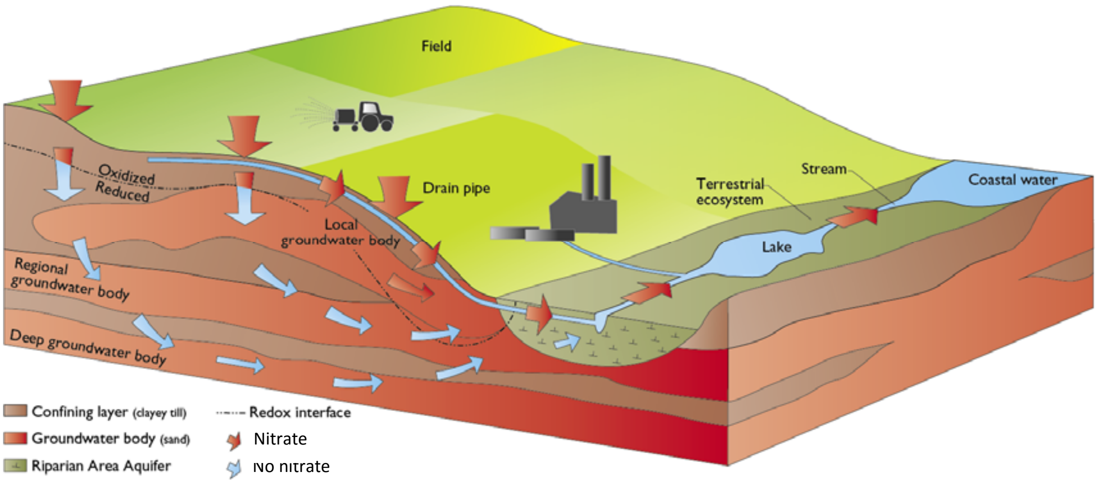

Figure 1. Concept of nitrate transport and reduction in groundwater and surface water. (Modified from Hinsby et al., 2008)

Due to geological heterogeneities this reduction of nitrate in groundwater and surface water systems shows large local spatial variations. This is illustrated in Figure 2 showing a calculated reduction map for a farm in the Norsminde catchment, Denmark. The figure reveals very large variations in the natural N-reduction, which can be exploited in a spatially differentiated regulation. Obviously, it will be waste of efforts to impose restrictions on handling of N on fields, where the natural N-reduction already removes more than 90% of the N-leaching from the root zone, while it will be much more cost-efficient to locate the mitigation measures on fields with N-reductions in the order of 30% or lower. Contrary to the traditional uniform regulation, the new concept of spatially targeted measures can exploit these heterogeneities in our natural environment. Hence, if we can predict, where in a catchment N is reduced along the flow path, then we can more cost-effectively design measures to reduce the nutrient loads to the Baltic Sea.

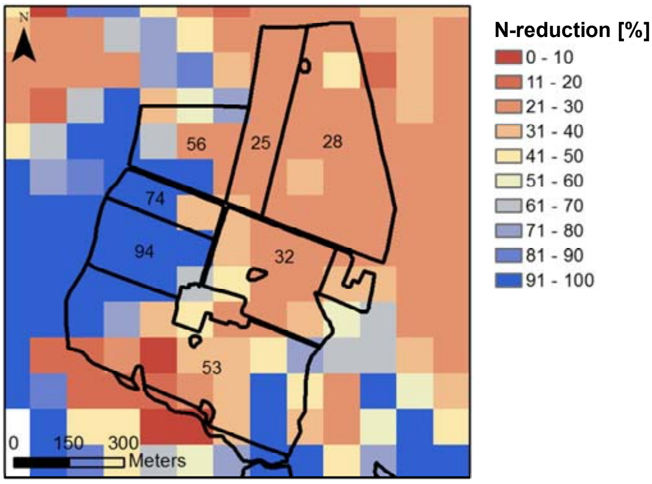

Figure 2. N-reduction map with a 100 m resolution for a part of the Norsminde catchment. The numbers displays the average N-reduction for specific fields (marked with black lines) (Jacobsen and Hansen, 2016).

The N-reduction maps, like the one shown in Figure 2, are typically calculated as average values for a given period. The N-reduction percentages somehow reflect the differences in flow paths for water particles originating from different fields. Thus those with a high reduction (blue cells in Figure 2) will typical have flow paths deep into the soils (like the left hand arrow in Figure 1), while the areas with low reduction (red cells in Figure 2) typically will have surface-near flow paths e.g. through tile drains. In the studies reported here the N-reduction maps have been assumed constant in time, which is a reasonable assumption when no changes in climate or crops are considered. In case of for instance climate change the amount of runoff will change. This will affect the split of runoff between groundwater recharge (the deeper flow path with high N-reduction) and drain pipe runoff (the surface-near flow path with low N-reduction) and hence the average N-reduction percentage will change.

3. Key findings and discussion

Studies were carried out for two Danish catchments: Norsminde (85 km^2) and Odense (486 km^2). A key tool in the analyses is N-reduction maps showing how much N is removed by natural reduction processes, i.e. the ratio between the N-load out of the catchment and the N-leaching from the root zone for each spatial unit within the catchment.

The details of the studies are reported in a paper and a manuscript in Appendices A and B.

The spatial targeting is then performed by considering the N-leaching (flux out of the root zone) and N-reduction (flux to the catchment outlet) in spatial units (100 and 200 m grids within the Norsminde and Odense catchments, respectively) and then relocate the units with largest N-leaching to the units with the largest N-reduction. In this way the natural N-reduction is maximised and the N-load out of the catchment is minimised. The gain of the spatial targeting is then the difference between the N-load for the actual location of the N-leaching and the N-load for the relocated N-leaching. The idea behind this is that the N-leaching is primarily determined by the crop rotation and is independent on the N-reduction occurring in the groundwater and hyporheic zones, and hence that the N-leaching can be relocated by management actions.

Thus, in other words the mitigation measure used to reduce the N-load is the relocate crops within the catchment, so that the reduction capacity of the subsurface below the root zone is exploited best possible. Some of the analyses in Appendices A and B then investigate how much the efficiency of the spatially targeting (relocation of crops) are decreased due to coarser resolution and uncertainty in the N reduction maps and due to constraints imposed by soil types, farm sizes, etc.

Some of the key findings from the two studies reported in Appendices A and B are summarised in Table 1.

Table 1. Reduction in N-loads obtained from relocation of crops for different assumptions on N-reduction map resolution, uncertainties and management constraints. All numbers are shown as percentage decrease in N-loads compared to business as usual N-load.

Resolution of N-reduction map	**Uncertainty**	**Agricultural management constraints**	**Nors-minde**	**Odense**
Norsminde: 100 m Odense: 200 m	None	None	8.0%	26%
Norsminde: 100 m Odense: 200 m	None	Crop relocation only within soil types	7.7%	22%
Norsminde: 100 m Odense: 200 m	None	Crop relocation only within farm boundaries	5.0%	17%
500 m	None	None	6.2%*	
1000 m	None	None	5.6%*	
Catchment	None	None	0%	
100 m	Uncertain N-reduction maps due to geological uncertainty	None	[6.1 - 7.4%]*	

* Numbers from additional model runs not shown in Appendix A

As can be seen from Table 1 the potential reduction in N-load (upper limit) achievable by using N-reduction maps at finest possible scale (100/200 m grids) assumed to be correct and imposing no agricultural management constraint is 8% in Norsminde and 26% in Odense. The large difference between the two catchments are due to i) differences in hydrogeology resulting in different N-reduction maps; ii) differences in farming structures; and iii) differences in N-leaching (in Odense catchment the spread in N-leaching between fields are considerably larger than in Norsminde).

Table 1 also shows the effects of practical agricultural management constraints. If crops cannot be relocated from one soil type to another, the efficiency of differentiated regulation drops marginally in Norsminde (from 8.0% to 7.7%), where one soil type covers most of the catchment, while the decrease in Odense having a wider diversity of soil types is larger (from 26% to 22%). If relocation of crops is not allowed over the entire catchment, but only within individual farms, the efficiency drops significantly, from 8.0% to 5.0% in Norsminde and from 26% to 17% in Norsminde.

The importance of using high-resolution N-reduction maps is also clear from Table 1. For Norsminde the gain drops from 8.0% (100 m maps) to 6.2% (500 m maps) and 5.6% (1000 m maps), while there is no gain left if the N-reduction is assumed constant throughout the catchment (uniform regulation).

The N-reduction maps are uncertain (Hansen et al., 2014). This has two key consequences: i) the decisions on cropping relocations will not be optimal and hence the real gain will be less than the potential gain; and ii) it is difficult to use the maps as a basis for a central government to impose regulations at field or even farm scale. The importance of the first aspect is illustrated in Table 1 for Norsminde by a decrease of gain from 8.0% to somewhere between 6.1% and 7.4%. These numbers only considers geological uncertainty that Hansen et al. (2014a) assessed to be the largest source of uncertainty. The 6.1% corresponds to the worst case using a single N-reduction maps among 10 different, equally plausible maps, while the 7.4% comes from a robust estimation of an N-reduction map based on the mean of the ensemble of 10 maps. The challenge related to the second aspect, i.e. which governance regime to use when considering the large uncertainties, is addressed in other BONUS SOILS2SEA deliverables (6.2, 6.3 and 6.4).

It must be noted that the present deliverable focuses on the gains of differentiated regulation within individual catchments, while the gain due to differences in N-reduction between catchments is not assessed. A previous study (Jacobsen and Hansen, 2016) assesses the gain due to variation between catchments in Denmark to be slightly smaller than the potential gain within a catchment analysed in the present deliverable. Jacobsen and Hansen (2016) assessed the economic gain achievable by differentiated regulation between catchments to correspond to a reduced cost between 16% and 27% equivalent to about 8 €/ha/year.

Altogether, it can be concluded that the potential gain from differentiated regulation in groundwater dominated catchments like in Denmark are considerably. In practice the uncertainties in N-reduction maps based on the existing data and practical agricultural management aspects will make it impossible to achieve the full potential. Furthermore, the large potential and the large uncertainties pose significant challenges to the governance regime.

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Appendix A

Potential benefits of a spatially targeted regulation based on detailed N-reduction maps to decrease N-load from agriculture in a small groundwater dominated catchment

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Potential benefits of a spatially targeted regulation based on detailed N-reduction maps to decrease N-load from agriculture in a small groundwater dominated catchment

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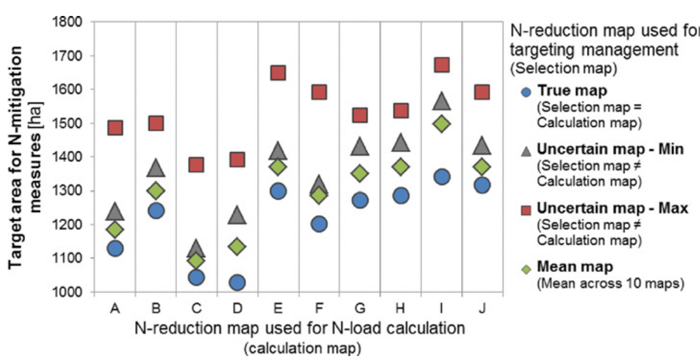
HIGHLIGHTS

- N-loads to coastal waters must be decreased and new ways of regulating are needed.
- A spatially targeted regulation focuses on areas with low natural N-reduction.
- A spatially targeted regulation has benefits over a spatially uniform regulation.
- Spatial resolution of the N-reduction map affects efficiency and benefits.
- Uncertainty on N-reduction map lowers efficiency of spatially targeted regulation.

GRAPHICAL ABSTRACT



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ABSTRACT

Denmark must further decrease the N-load to coastal waters from agricultural areas to comply with the Baltic Sea Action Plan and the EU Water Framework Directive. A new spatially targeted regulation is under development that focuses on locating N-mitigation measures in areas with low natural reduction of nitrate (N-reduction). A key tool in this respect is N-reduction maps showing how much N is removed by natural reduction processes, i.e. the ratio between the N-load out of the catchment and the N-leaching from the root zone for each spatial unit within the catchment. For the 85 km^2 groundwater dominated Norsminde catchment in Denmark we have analysed the potential benefits of a spatially targeted regulation and how its efficiency is affected by uncertainty in the N-reduction map. Our results suggest that there are potential benefits of implementing a spatially targeted regulation compared to a spatially uniform regulation. The total N-load at the catchment outlet can be decreased up to 8% by relocating the existing agricultural practice according to the N-reduction map and thus without decrease fertilization inputs. A further decrease in N-load can be obtained by identifying target areas with low N-reduction where N-mitigation measures must be applied. Uncertainty on the N-reduction map is found to lower the efficiency of spatially targeted regulation. This uncertainty can be lowered substantially by using the mean of an ensemble of N-reduction maps. The uncertainty decreases with coarser spatial resolution of the N-reduction map, but this will at the same time decrease the benefit from spatially targeted regulation.

1. Introduction

Eutrophication has been a severe environmental problem in the Baltic Sea during the past decades due to high loads of the nutrients

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Appendix B

Spatially differentiated strategies for reducing nitrate loads from agriculture in two Danish catchments

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Research article

Spatially differentiated strategies for reducing nitrate loads from agriculture in two Danish catchments

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ABSTRACT

Nutrient loss from agriculture is the largest source of diffuse water pollution in Denmark. To reduce nutrient loads a number of solutions have been implemented, but this has been insufficient to achieve the environmental objectives without unacceptable repercussions for agricultural production. This has substantiated the need to develop a new approach to achieve nitrogen (N) load reduction to the aquatic environments with lower costs to farmers. The new approach imply targeting N leaching mitigation to those parts of the landscape which contribute most to the N-loadings. This would involve either reducing the source loading or enhancing the natural reduction (denitrification) of N after it is leached from the root zone of agricultural crops. In this study, a new method of spatially differentiated analysis for two Danish catchments (Odense and Norsminde) was conducted that reach across the individual farms to achieve selected N-load reduction targets. It includes application of cover crops within current crop rotations, set-a-side application on high N-load areas, and changes in agricultural management based on maps of N-reduction available for two different spatial scales, considering soil type and farm boundaries as spatial constraints. In summary, the results revealed that considering spatial constraints for changes in agricultural management will affect the effectiveness of N-load reduction, and the highest N-load reduction was achieved where less constraints were considered. The results also showed that the range of variation in land use, soil types, and N-reduction potential influence the reduction of N-loadings that can originate from critical source areas. The greater the spatial variation the greater the potential for N load reduction through targeting of measures. Therefore, the effectiveness of spatially differentiated measures in term of set-a-side area in Odense catchment were relatively greater compared to Norsminde catchment. The results also showed that using a fine spatial N-reduction map provides greater potential for N load reductions compared to using sub-catchment scale N-reduction maps.

1. Introduction

In Denmark, agricultural activities is the major contributor of nitrate to the coastal waters. This is a consequence of the large extent of agriculture (more than 60% of land is farmed) and short distances between agricultural source areas and the coastline (Dalgaard et al., 2014). This has resulted in deterioration of the quality of groundwater and surface waters. Since 1985, several action plans have been implemented in Denmark to reduce N discharges from point sources and diffuse losses from agriculture (Kronvang et al., 2008). In particular, the implementation of the EU Nitrates Directive required accounting for the fertilizer value of N in manure, and limiting N application to what was required for crop yield and N removal (Van Grinsven et al., 2012). The N-regulation in Denmark was until 2015 based on N fertilizer quotas for field application based on crops and soil type, time management rules for slurry and manure application and mandatory cover crops (Dalgaard et al., 2014). Although measures like wetlands, buffer strips and 2 m riparian zones along streams and lakes are to some extent site specific, current regulation of N fertilization is mainly input-based and applied uniformly for the whole of Denmark.

This N-regulation in Denmark is largely applied without considering the required N-load reduction targets for a given catchment and the spatial variability in the natural N-reduction in

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