

ON THE TRACK OF TARGETED REGULATION OF NITRATE – EXPERIENCES FROM DENMARK

Anker Lajer Højberg

Geological Survey of Denmark and Greenland

Øster Voldgade 10, 1350 Copenhagen K

E-mail: alh@geus.dk

Abstract

European member states must comply with the EU Water Framework Directive (WFD) on reaching a good ecological status for all waters. A major challenge in this ambitions goal is to lower nutrients loads to the coastal waters to reduce the risk for eutrophication. Nitrate comprise the largest problem in many fjords and estuaries in Denmark, where it is estimated that approximately 90% of the load is from diffuse sources, primarily agriculture. Historically, the Danish nitrogen regulation has been based on a uniform approach, imposing the same restrictions for all areas independent on drainage schemes, hydro-geochemical conditions in the subsurface and retention in surface waters. Although this regulation, implemented in several national action plans since the mid-eighties, has been successful in nearly halving the nitrogen loads to the marine recipients, further abatements are required. A uniform regulation is not cost-effective, as the vulnerability of the individual marine recipients are different, and the nitrogen is reduced naturally, but with large spatial variations depending on the local transport pathways and the hydro-geochemical conditions. New and innovative regulation approaches therefore need to be developed that utilises this natural variation, and targeted and spatially differentiated regulation has been intensively debated in Denmark in the past five years. Presently, new nitrogen measures are implemented at catchments scale, for which the farmers are compensated, and this will be complemented by a targeted regulation in 2019. The strategy for targeted regulation has not been defined in details, but several recent national projects have been devoted to study how spatial variation can be identified at relevant scale with sufficient certainty and included in national regulation. The paper draws on results from some of these studies with emphasis on transport and degradation in the subsurface system, where the largest natural reduction occurs, and the importance of the redox conditions, drainage conditions and riparian lowlands.

Danish conditions

Denmark covers 43.000 km² land area and with approximately 60% agriculture is by far the most dominant land use. Most of the agricultural area (~90%) is arable land with intensive farming praxis. Almost 20 million pigs are produced per year for slaughtering and another 13 million piglets are produced for export, making Denmark one of the most intensive pig producers in the world relative to the area.

Denmark has a humid climate with yearly rainfall ranging between 500 to 900 mm. While water deficit is experienced in some summer months, excess rainfall in fall, winter and spring provides substantial infiltration to groundwater aquifers used as the only drinking water resource. In

many parts, the groundwater table are located close to the surface and with 1-1.5 m seasonal fluctuation in the groundwater table, approximately 50% of the cultivated land is artificial drained to ensure good crop production.

Intensive farming are accompanied by high nitrate utilisation rates. Although the nitrate uptake by plants have been improved in recent years, it is estimated that only about 40% of nitrate applied in the field is utilised by the plants, while the rest are stored in the soil pool, being denitrified or lost to the aquatic environment by leaching from the root zone.

Combating nitrate

As part of EU, Denmark must comply with the EU Water Framework Directive (WFD), where the goal is to obtain a good ecologic status of all waters. The WFD was implemented in 2000, but preceded by Danish national action plans (AP) of which the first was adopted as early as 1987 followed by subsequent action plans and plans for sustainable agriculture (APSA) and Green growth (GV), Figure 1.

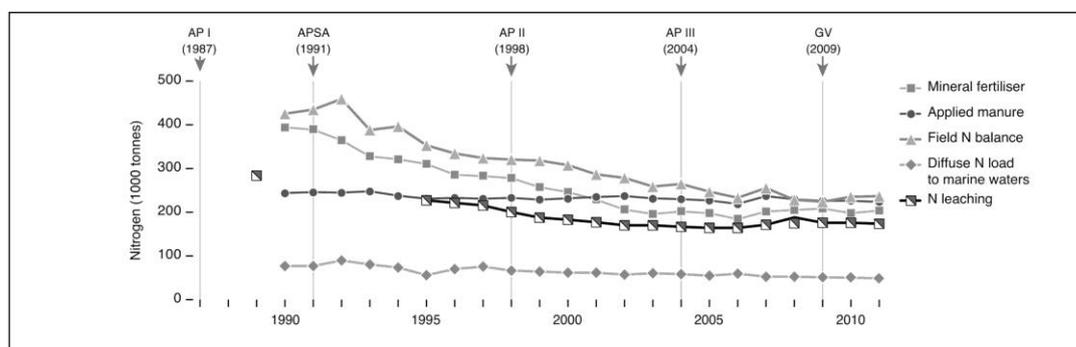


Figure 1: National N-leaching from the root zone, field N-balance, consumption of mineral N-fertilisers and applied N in manure for the Danish agricultural area and N-loading to marine waters from diffuse sources. Action Plan for the Aquatic Environment I–III (API-III), Action Plan for a Sustainable Agriculture (APSA) and Action Plan for Green Growth (GV). From (Blicher-Mathiesen et al., 2014).

The national action plans have been successful in nearly halving the diffuse nitrate load to the marine waters. This was achieved by enforcing a combination of good management practises and restrictions, such as mandatory slurry tanks, restrictions for when slurry can be spread, mandatory crop and fertiliser plans together with mandatory buffer strips and use of catch crops, but also reduction in the rate of fertiliser that can be applied (reduced N-norm), where application of plant-available N to crops was reduced in action plan APII to 10% below the economic optimal value. Common to all actions was that a uniform approach was adopted, i.e. the same restriction was imposed all over regardless of the physical characteristic, such as drainage system and hydrogeological conditions.

The EU WFD is implemented by River Basin Management Plans (RBMP), where the first covering the period 2009-2015 was adopted in 2014, i.e. close to the end of the period. An important reason for the late adoption was that the technical basis for the plan was questioned, particularly that the plans did not consider the local conditions and was based on a too simple approach and tools. Concurrent to this process a national commission on Nature and Agriculture was established by the Danish government to identify new approaches to ensure efficient farming praxis while at the same time improving the environment. One of the most important

recommendations from the commission was to take a differentiated and targeted approach, where restrictions are focused to areas where reduction are needed and have the most effect. This approach starts by identifying the vulnerabilities of the receiving recipients (marine areas and groundwater aquifers) and assess the total abatement needed to reach a good ecological status. In areas where abatement is needed, the next step is to identify the natural attenuation capacity in the landscape and impose the restrictions in areas where the attenuation is low.

To improve the assessments for the second RBMP covering the period 2015-2021, the Danish Environmental and Agricultural agencies initiated a strategic model project, with the aim of developing improved modelling tools to assess the vulnerability of the marine areas (marine models), status of the lakes (lake models) and assessment of the spatial variability in natural attenuation of nitrate at a national scale.

The Danish national nitrogen model

The first version of a national N-reduction map was developed in 2006 (Ernstsen et al., 2006), based on estimates of the total N-leaching from the root zone within a catchment and the N-load observed in the stream at the catchment outlet. This resulted in a map with a generally coarse and inhomogeneous scale with catchment areas ranging from below 5 to more than 2,500 km². In order to utilise the attenuation at a smaller and more homogenous scale a national nitrogen model was developed.

The national nitrogen model (NNM) is constructed by coupling three existing modelling systems describing transport and reduction in the Root zone; groundwater; and surface waters:

1. *Root zone.* N-leaching from the root zone is estimated by the NLES model (Simmelsgaard and Djurhuus, 1998), which is a statistical model developed on the basis of data from field trials, where nitrate leaching has been measured one meter below the surface. The model calculates annual leaching values, which is disaggregated to daily values using the soil-plant-atmosphere model Daisy (Hansen et al., 2012).
2. *Groundwater.* Flow and transport from the root zone to the surface water system is simulated by the Danish national water resources model: DK-model (Højberg et al., 2013). It is an integrated surface- and groundwater model accounting for the major hydrological processes on the land phase. The model is constructed in the physically based and fully distributed modelling system MIKE SHE/ MIKE 11 (Havnø et al., 1995). Description of flow and transport in the groundwater system rely on a three-dimensional interpretation of the subsurface hydrogeology and the model is able to simulate flow and transport from land surface to the surface water system and further to marine areas.
3. *Surface water.* Statistical models are employed to describe retention and reduction of nitrate in streams, wetlands and lakes. These models have been developed and tested as part of the Danish National Environmental and Nature Monitoring Programme (NOVANA) (Windolf et al., 2011). Input to the surface water systems consists of N transported via the groundwater and additional point sources that discharges directly to the streams. Data for point sources are collected from national databases.

Reduction of nitrate to free nitrogen gas by denitrification will only take place in reduced environments, where no (or very limited) oxygen is available as electron acceptor. The geochemical conditions, and its spatial variability, thus becomes very important in accessing natural attenuation. The geochemical condition of the subsurface in Denmark is generally characterised by an upper oxic part and a lower reduced part that is separated by a redox-interface. Estimating the nitrate reduction in the subsurface is thus accomplished in the NNM by using a particle tracking method to describe the transport pathways, and identify if particles

crosses the redox-interface. Although the reaction rate for denitrification can be kinetically controlled, the process can for practical purposes generally be assumed instantaneous compared to the long groundwater travel times. Nitrate entering the lower reduced environment in the subsurface are thus assumed to be removed by denitrification.

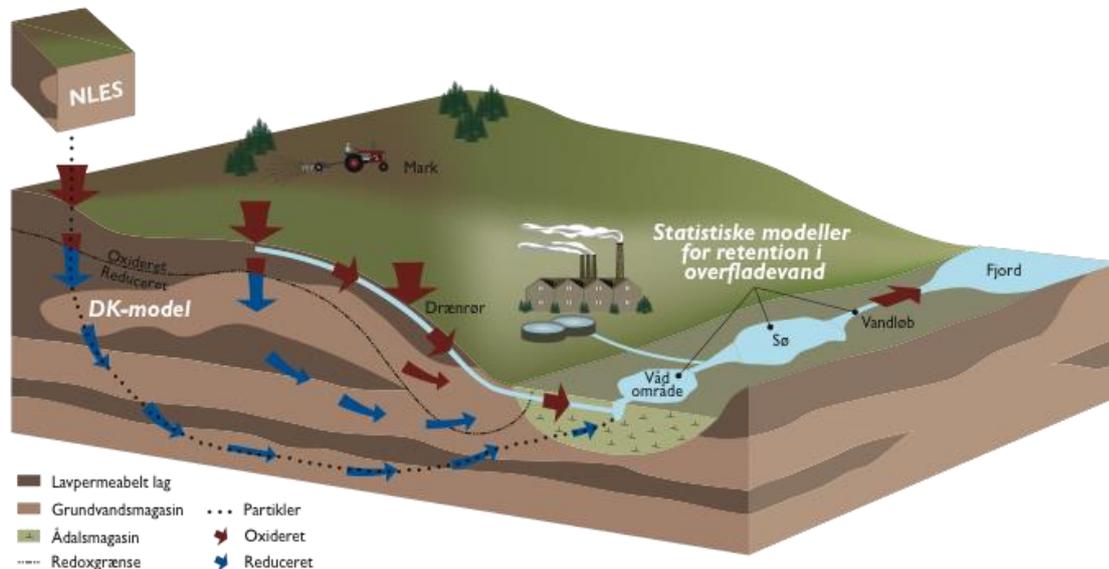


Figure 2: Concept figure of the Danish national nitrogen model (from Højberg et al., 2015)

Applying the model in “forward” mode nitrate transport from the soil to the marine areas are calculated, taking reduction in surface- and groundwater into account. The model can also be worked backwards, to provide estimates of where and how much nitrate is reduced in the different compartments. This have been utilised to develop national N-reduction (or attenuation) maps, showing the percentage nitrate being reduced during transport in: 1) groundwater, 2) surface water, and 3) the entire transport from the surface to the marine environment.

Studies have shown that the cost-effectiveness of targeted regulation increases for a decreasing spatial scale (Hansen et al., 2017), and it would thus be desirable to map the natural attenuation at the field scale. However, other studies have illustrated how the uncertainty in the estimates of natural attenuation increases for decreasing scale (Hansen et al., 2014). There is thus a trade-off between the cost-effectiveness and the uncertainty. While there was a certain wish to map the N-reduction at field scale, it was documented that this would be too uncertain given the available data, knowledge, models and time for developing the NNM.

The model was calibrated and validated against observed N-transport from ca. 340 catchments. Most observations are located downstream close to the outlet to the sea. This location has been selected to maximise the area covered by the monitoring stations, which also means that many observed catchments are very large. The minimum observed catchment size with good reliable data over a longer period is approximately 15 km², which is thus the scale at which the model can be confronted with data, and model uncertainty addressed from data. It was thus decided that model results should not be utilised at a smaller, and the resulting N-reduction was established for topographical catchments with a mean size of approximately 15 km², as illustrated in Figure 3 for the N-reduction map displaying the entire reduction from field to sea.

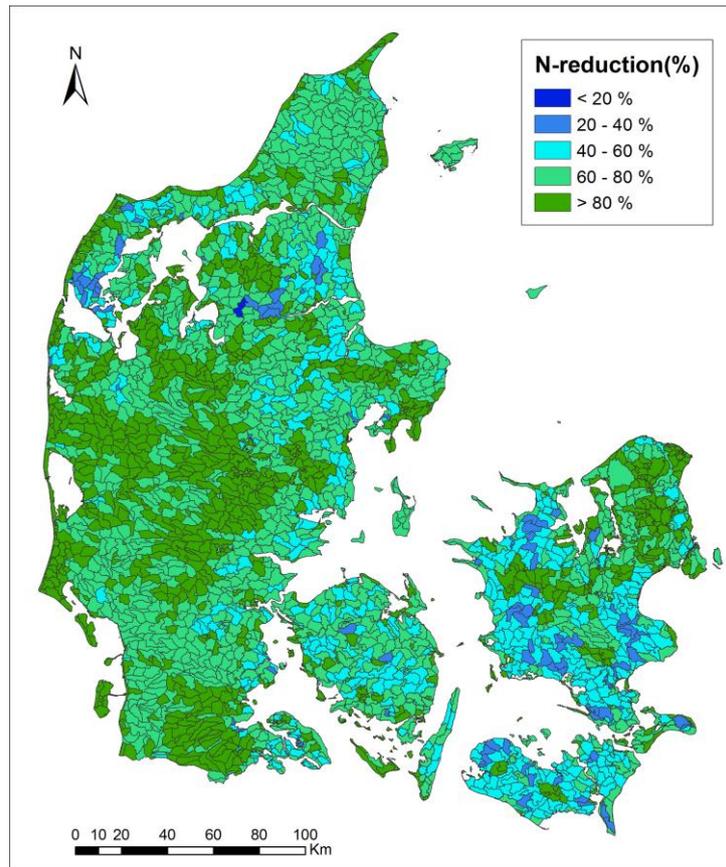


Figure 3: National N-reduction map displaying estimated nitrate reduction in percent from field to the sea.

Two main issues prevented a direct utilisation of the N-reduction map for regulation of individual farmers: 1) The map display the mean N-reduction within the ID15 catchments, but not the variation within. Hence, variation between the ID15 can be used to focus on specific areas, but at smaller scale there will be significant variations between fields and farms. Imposing rigid regulation at the ID15 level would result in too strict regulations in some areas, and too little in others, 2) The variation in the natural attenuation is caused by heterogeneities in hydrogeological and geochemical conditions, these may vary over small distances, which cannot be mapped in detail, leading to an inherent uncertainty in the map.

Next generation of regulation

In 2016 a Food and Agricultural Package was adopted by the Danish government. The packaged includes the removal of some historical N-mitigation measures, such as the reduced N-norm and mandatory buffer strips. At the same time the package introduced a new approach to regulation with two general instruments: 1) Collective measures, and 2) Targeted regulation. The main features of the Food and Agricultural packages are summarised in Table 1.

Table 1: The main features of the Food and Agricultural packages.

Food and Agricultural packages	
Measures	<p>Removal/change of historical measures</p> <ul style="list-style-type: none"> • Removal of N-norm below economic optimum • Removal of mandatory buffer strips • Change in rules for catch crops <p>Replacements</p> <ul style="list-style-type: none"> • Additional catch crops until new measures in collective and targeted regulation are effective • Encouraging the development of new measures to provide more flexibility for the farmers. New measures needs to be validated.
Collective measures	<p>Features</p> <ul style="list-style-type: none"> • Catchment basis, i.e. measures implemented will benefit all farmers within the catchment • Voluntary • Full compensation <p>Measures</p> <ul style="list-style-type: none"> • Primary “off-field” measures, such as wetland, constructed mini-wetlands
Targeted regulation	<p>Features</p> <ul style="list-style-type: none"> • Farm basis, only the farmer implementing the farmer will benefit • Regulated • No compensation <p>Measures</p> <ul style="list-style-type: none"> • Primary “on-field” measures, such as catch crops and reduced N-norm, and possible new validated measures

The collective measures are being implemented in the period 2018-2020, including an estimated 1,000 new constructed wetlands. Early 2018 a final agreement was made by the majority in the Danish parliament on introducing targeted regulation from 2019. The strategy for implementing targeted regulation is not yet known in details, but the overall strategy is to prioritise areas where most N-reduction is required. Within these areas the implementation of measures will be voluntary and compensated. If sufficient reduction is not reached by voluntary measures, the remaining reduction will be obtained by regulation, where the same regulation are imposed all over, with no compensation. The agreement acknowledge that new knowledge and additional data are established continuously, which should be included in the future with the goal of making the targeted regulation more differentiated and to the extent possible include monitoring data. The agreement further envisions a higher degree of local involvement and a higher degree of flexibility in N-mitigation measures.

The location of measures introduced by the Food and Agricultural package has been prioritised using the N-reduction map. By this the use of catch crops has been maximised in areas where the groundwater reduction is low and constructed wetland in areas where the surface water retention is low. In a similar way, the N-reduction map is anticipated to be the backbone for prioritising the targeted regulation from 2019.

Improving the assessments

The last five years intensive debate on targeted N-regulation in Denmark has supported the initiation of a number of new research and development projects, focussing at various aspects including natural, economic, social and socio-economic science. At the natural science, focus has been on how it is possible to identify/map the natural heterogeneity and account for the effects of this heterogeneity at national scale.

One of these projects is “TReNDS – Transport and Reduction of Nitrate in Danish Landscapes at various Scales” (www.nitrat.dk), with the overall aim of improving our understanding and develop the scientific foundation, field technologies and modelling concepts for cost-effective quantitative assessments of nitrate transformation at various landscapes required for spatially differentiated regulation. To achieve this, TReNDS focuses on five topics (Figure 4):

1. **Tile drains.** Drains provides a fast circuit between the root zone and the surface water system, allowing limited reduction of nitrate on its way. Approximately 50% of the arable land in Denmark is artificially drained, but with large variation from place to place and with large variation in the effectiveness of the drains. Information on the drain location is limited, and ground penetrating radar in combination with electromagnetic (DUALEM) measurements are used to identify drainage network. This method has proved successful under some conditions, but are found sensitive to the clay and soil moisture content. Drainage dynamics are assessed from observed drain flow and field scale tracer experiments, which is analysed by detailed numerical modelling, with focus on developing an upscaled methodology to improve representation of drainage in catchment scale models.
2. **Riparian lowlands.** Lowlands are complex environments that can have significant impact on the catchment scale nitrate balance. Many lowlands are characterised by high organic matter content and thus have the potential of providing an effective reactor, removing nitrate before it discharges to the streams. However, local hydrological and hydrogeological conditions controls if water, and nitrate, is transported through the lowland reactors, or bypasses as overland flow, with too little time for reaction to take place. Intensive monitoring in two lowland areas representing contrasting hydro-geochemical conditions have provided detailed insight in the complex interaction between water flow paths and reducing compounds, and its importance on the hydro-biogeochemical transformation of nitrate in riparian lowlands. While the reducing compounds of the lowlands can be mapped, the local flow path can only be addressed by proxy data, and numerical modelling is utilised to study how various lowland characteristics (e.g. catchments size, hydrology and hydrogeology) influence discharge and N-reduction.
3. **Subsurface redox conditions.** Reduction of nitrate by denitrification in the groundwater zone is responsible for the majority of the natural nitrate removal on its transport from the root zone to the deeper aquifers and the marine areas. Denitrification occurs in anoxic environments, which dominates in the lower part of the subsurface. Mapping the interface between the oxic and anoxic parts (the redox interface) is thus of great importance. A new redox-probe has been developed in TReNDS that can provide many new measurements of the redox interface in a cost-effective way. Furthermore, a new method has been developed to construct a national map of depth to the redox interface that can be easily updated to adopt local scale measurements. Furthermore, local scale data provide information on the spatial variability of the redox interface, which is utilised to address the uncertainty related to the imperfect knowledge on its location.

4. **Integrated modelling.** In order to support an advancement of targeted regulation at the national scale, the detailed knowledge obtained at the field sites must be upscaled for use in integrated catchment scale and national modelling. Combining field data and analyses of detailed small scale modelling, different approaches are tested in catchment scale models with focus on improving the simulation of the amount of drain flow generated at sub-catchment scale, roughly 15 km², and within the same scale represent the effectiveness of the N-reduction in lowlands. New methods to include more local knowledge from drain stations in model calibrations is further analysed.
5. **Local knowledge and data.** The regulation in Denmark has traditionally been centralised and top-down controlled. With the new principles laid down for spatial regulation, it is the vision to further develop the targeted regulation in a direction where more local knowledge and data can be included. TReNDS supports this by working closely with farmers. Simple and hand-held instruments for collecting observation in drainage and stream water have been tested for accuracy and usability in the field. Further, pros and cons on new possible governance structures have been discussed at dedicated workshops, together with specific possibilities for the third cycle of the WFD.

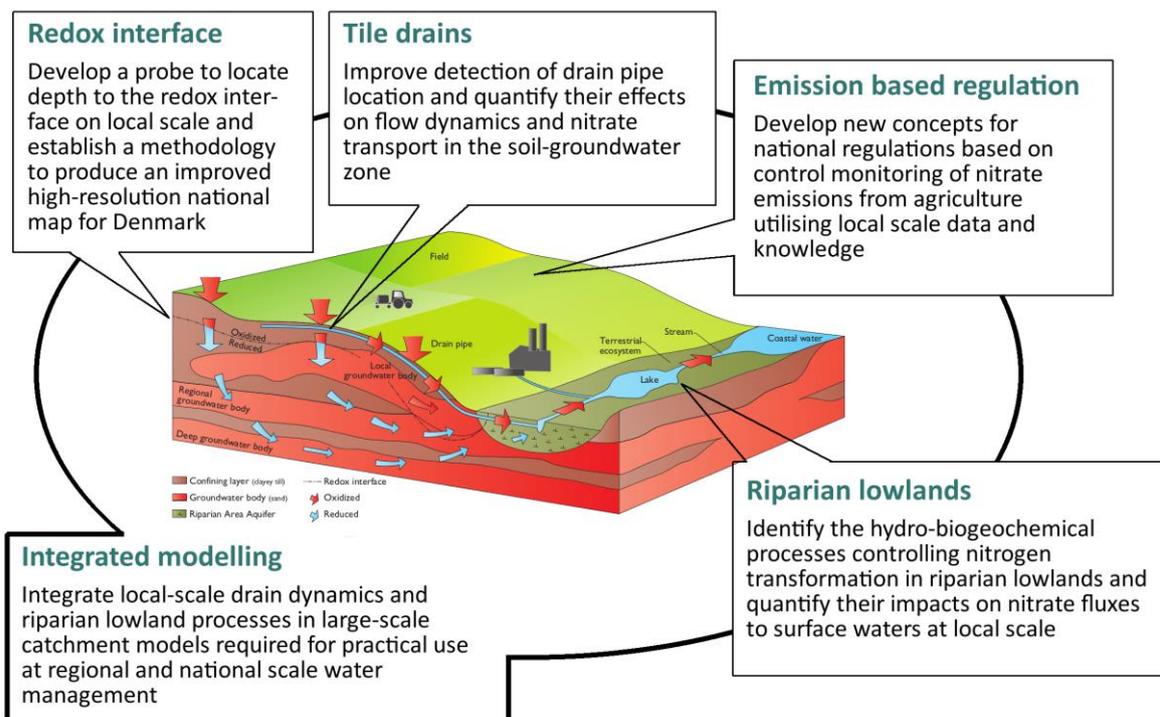


Figure 4 Topics covered in the research project TReNDS.

Future perspectives

In the coming years the differentiated and targeted regulation is to be implemented. The overall strategy has been described in the agreement on targeted regulation, but needs to be detailed and further developed. It is anticipated that the national N-reduction map will be central in developing the targeted approach. It is, however, also acknowledge that substantial new knowledge has been obtained from the large number of research projects that have been funded in recent years, with focus on supporting a spatial differentiated regulation of nitrate. The N-

reduction map is thus likely to be updated prior to its application. An interesting and, seen from the research side, a much appreciated element of the agreement is that it acknowledge that new knowledge and data are continuously being established, which can be utilised to improve the regulation in the future.

Acknowledgement

The work has been carried with financial support granted by the TReNDS research project funded by the Innovation Fund Denmark (grant no. 4106-00027B)

Reference

- Blicher-Mathiesen, G., Andersen, H.E., Carstensen, J., Børgesen, C.D., Hasler, B., Windolf, J., 2014. Reprint of “Mapping of nitrogen risk areas.” *Agric. Ecosyst. Environ.* 198, 83–93. doi:10.1016/j.agee.2014.06.031
- Ernstsen, V., Højberg, A.L., Jakobsen, P.R., Platen-Hallermund, F. v., Tougaard, L., J.R., H., Blicher-Mathiasen, G., Bøgestrand, J., Børgesen, C.D., 2006. Beregning af nitrat-reduktionsfaktorer for zonen mellem rodzonen og frem til vandløb. Data og metode for 1. generationskortet.
- Hansen, A.L., Gunderman, D., He, X., Refsgaard, J.C., 2014. Uncertainty assessment of spatially distributed nitrate reduction potential in groundwater using multiple geological realizations. *J. Hydrol.* 519, 225–237. doi:10.1016/j.jhydrol.2014.07.013
- Hansen, A.L., Refsgaard, J.C., Olesen, J.E., Børgesen, C.D., 2017. 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. *Sci. Total Environ.* 595, 325–336. doi:10.1016/j.scitotenv.2017.03.114
- Højberg, A.L., Trolborg, L., Stisen, S., Christensen, B.B.S., Henriksen, H.J., 2013. Stakeholder driven update and improvement of a national water resources model. *Environ. Model. Softw.* 40. doi:10.1016/j.envsoft.2012.09.010
- Windolf, J., Thodsen, H., Trolborg, L., Larsen, S.E., Boegestrand, J., Ovesen, N.B., Kronvang, B., 2011. A distributed modelling system for simulation of monthly runoff and nitrogen sources, loads and sinks for ungauged catchments in Denmark. *J. Environ. Monit.* 13, 2645–2658. doi:10.1039/c1em10139k