DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/67**

Prioritization tool for implementing the N-MAP concept

Denitza D. Voutchkova, Anders V. Christiansen, Anker L. Højbjerg, Bo V. Iversen, Brian H. Jacobsen, Eva Willerslev, Gitte Blicher-Mathiesen, Helle M. Holm, Ingelise Møller, Julian Koch, Kenneth Nygaard, Line B. Nørgaard, Lærke Thorling, Peter B.E. Sandersen, Stefan Schaper, Søren K. Hvid, Tommy Dalgaard & Birgitte Hansen

DE NATIONALE GEOLOGISKE UNDERSØGELSER
FOR DANMARK OG GRØNLAND
KLIMA-, ENERGI- OG FORSYNINGSMINISTERIET

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/67**

Prioritization tool for implementing the N-MAP concept

Denitza D. Voutchkova, Anders V. Christiansen, Anker L. Højbjerg, Bo V. Iversen, Brian H. Jacobsen, Eva Willerslev, Gitte Blicher-Mathiesen, Helle M. Holm, Ingelise Møller, Julian Koch, Kenneth Nygaard, Line B. Nørgaard, Lærke Thorling, Peter B.E. Sandersen, Stefan Schaper, Søren K. Hvid, Tommy Dalgaard & Birgitte Hansen

Editors: Denitza D. Voutchkova and Birgitte Hansen

DE NATIONALE GEOLOGISKE UNDERSØGELSER
FOR DANMARK OG GRØNLAND
KLIMA-, ENERGI- OG FORSYNINGSMINISTERIET

G E U S

Ministry of Environment of Denmark
Environmental Protection Agency

SEGES

AARHUS UNIVERSITY

UNIVERSITY OF COPENHAGEN

Innovation Fund Denmark

DE NATIONALE GEOLOGISKE UNDERSØGELSER FOR DANMARK OG GRØNLAND
KLIMA-, ENERGI- OG FORSYNINGSMINISTERIET

G E U S

Fact sheet:

Title:	**Prioritization tool for implementing the N-MAP concept**
Authors:	Denitza D. Voutchkova, Anders V. Christiansen, Anker L. Højberg, Bo V. Iversen, Brian H. Jacobsen, Eva Willerslev, Gitte Blicher-Mathiesen, Helle W. Holm, Ingelise Møller, Julian Koch, Kenneth Nygaard, Line B. Nørgaard, Lærke Thorling, Peter B.E. Sandersen, Stefan Schaper, Søren K. Hvid, Tommy Dalgaard & Birgitte Hansen
Editors:	Denitza D. Voutchkova and Birgitte Hansen
Institutions:	Geological Survey of Denmark and Greenland (GEUS) Aarhus University (AU): Department of Agroecology, Department of Geoscience, Department of Bioscience, Department of Management Copenhagen University (KU): Department of Food and Resource Economics SEGES/Rambøll
Publisher:	Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, 1350 København K, Denmark
Publishing date:	November 2021
Editing finalized:	February 2022
Scientific proofreading:	Thomas Vangkilde-Pedersen, GEUS
Language proofreading:	Caroline Dea Rutter
Please cite:	Voutchkova, D.D., Christiansen, A.V., Højberg, A.L., Iversen, B.V., Jacobsen, B.H., Willerslev, E., Blicher-Mathiesen, G., Holm, H.W., Møller, I., Koch, J., Nygaard, K., Nørgaard, L.B., Thorling, L., Sandersen, P.B.E., Schaper, S., Hvid, S.K., Dalgaard T. & Hansen, B., 2021. Prioritization tool for implementing the N-MAP concept. Eds.: Voutchkova, D.D. & Hansen, B. Geological Survey of Denmark and Greenland. GEUS report 2021/67.
ISBN:	**988-87-7871-560-9** (print); **978-87-7871-562-3** (online)
Number of pages:	**69**

Online version: https://eng.mapfield.dk/

Contents

1 Summaries

1.1 English summary

This report is initiated in the context of the Innovation Fund Denmark project MapField running from 2018-2022 (https://eng.mapfield.dk/). The purpose is to describe a prioritization tool on an ID15 (approximately 1500 ha) catchment level that can assist in selecting, which areas are most suitable for implementing the new concept (called N-MAP) to support targeted N-regulation of agriculture to harvest the largest possible benefits for both the environment and the agricultural production.

The N-MAP concept is based on the collection, interpretation, and modelling of large amounts of data to precisely calculate the transport and turnover of water and nitrogen (N) in the subsurface. The result is a high-resolution map of the N-retention in the subsurface, e.g. at field scale with a relatively low uncertainty.

The prioritization tool is developed through an iterative process with internal and external experts (contributing authors of the report) in workshops and individual meetings, eliciting knowledge on specific issues, and finally, based on comments on the first version of this report. The aim has been to reach a consensus, or an optimal compromise, as evaluated by the editors.

There needs to be variation in the N-retention between fields within the administrative ID15 catchments before it becomes viable to implement targeted regulation of the N-fertilization and management at field level. Therefore, the following decisions were made regarding prioritization of the ID15 catchments for implementation of the N-MAP concept:

- The higher the heterogeneity in the subsurface geology and redox conditions, the higher the priority.

Secondly, it was decided to use a binary approach regarding the following conditions:

- A high degree of N-retention in the surface water system means that the areas are excluded.
- A high degree of N-flow directly to drains and ditches from the agricultural fields means that these areas are excluded.
- All areas with N-reduction demands are included, while areas with no demands are excluded.

The prioritization tool is implemented through a three-step, hierarchical composite indicator approach using postponed N-reduction demands from The River Basin Management Plan II (VPII) and scoring of five selected themes on 1) geological complexity and 2) redox complexity, combined in Step 1, 3) N-retention in surface waters and 4) degree of drainage combined in Step 2, and 5) N-reduction demands in Step 3. This hierarchical approach was selected because it is flexible and allows for stepwise changes. For example, when the N-reduction demand for VPIII is known, only Step 3 would need to be revised.

The eight case studies from rOPEN (Javngyde and Sillerup) and MapField (LOOP 2, 3, 4 and 6, and the two demo sites at Salling) were used for demonstrating the performance of the prioritization tool according to the five themes. Each of the eight case studies consist of 1-3 ID15 catchments. Javngyde has the highest score of all the eight case studies, with a total score of 0.8 due to high geological and redox complexity, and Sillerup has the lowest total score of zero because of a high degree of N-transport in drains. LOOP 2, located in Himmerland, has a low total score of 0.2 because of a relatively low redox complexity. LOOP 3 at Ejer Bavnehøj also has the lowest total score of zero in ca. 45% of the area because of a high fraction of N-transport in drains in two of the ID15 catchments in the study case. The remaining 55% of the case study has a total score of 0.48 because of medium high score in geological complexity (score T1 0.8) and medium redox complexity (score T2 = 0.6). LOOP 4 at Lillebæk on Funen has total scores ranging from 0-0.48 because of different degrees of drainage and redox complexity. LOOP 6 at Bolbro in Southern Denmark has total scores ranging from 0-0.64 because of different degrees of geological and redox complexity, and drainage in the area.

The developed prioritization tool focuses on surface waters and protection of coastal areas. However, a similar prioritization tool that focuses on groundwater protection can be developed based on a similar composite index method, but only including themes appropriate for groundwater protection.

The high-resolution mapping and modelling of the eight case studies in rOPEN and MapField projects revealed higher subsurface complexity than previously known. Therefore, existing data exhibited limitations on the evaluation of the local complexity before implementing the N-MAP concept.

Uncertainties and limitations related to the selected five themes are discussed, and all themes are preliminary in the sense that the themes should be updated with new knowledge. Especially, the experience from MapField shows that redox complexity and architecture is not the only important geochemical parameter for assessing the N-retention in the subsurface. The N-reduction rate is also very important, but this parameter cannot be taken into consideration in the prioritization tool on a national level due to lack of knowledge. However, with time and an increasing number of areas coved by detailed mapping in the coming years it might be possible to include this parameter as well.

The prioritization tool and the final prioritization map come with an uncertainty than depends on the uncertainty, aggregation, and scoring of the five individual themes. This prioritization tool should also be seen as the first version of a prioritization tool which can be updated and refined when more knowledge and data become available with time and with an increasing number of areas covered with detailed mapping in the coming years.

1.2 Danish summary

Denne rapport er initieret i projektet MapField støttet af Innovationsfonden, som forløber fra 2018-2022 (http://mapfield.dk/). Formålet er at beskrive et prioriteringsværktøj på et ID15-oplandsniveau (ca. 1500 ha), der kan bruges til at udvælge, hvilke områder der er bedst egnede til at implementere det nye koncept (kaldet N-MAP). Implementeringen af N-MAP skal understøtte målrettet N-regulering af landbruget med henblik på at opnå de største sandsynlige fordele for både miljøet og landbrugsproduktionen.

N-MAP-konceptet er baseret på indsamling, fortolkning og modellering af store mængder data for præcist at beregne transport og omsætning af vand og kvælstof i undergrunden. Resultatet er et højopløseligt kort over N-retentionen i undergrunden på fx hektarskala med en relativt lav usikkerhed.

Prioriteringsværktøjet er udviklet gennem en iterativ proces med interne og eksterne eksperter (forfattere til rapporten) på workshops og individuelle møder, hvor specifikke problemstillinger er diskuteret, og valg er foretaget. Ligeledes er der i den endelige version af rapporten taget højde for kommentarer til en første version. Målet har været at nå frem til en konsensus eller et optimalt kompromis baseret på en vurdering af de to editorer.

Der skal være variation i N-retentionen mellem marker inden for det administrative ID15-opland, før det er omkostningseffektivt at implementere målrettet N-regulering og forvaltning på markniveau. Derfor blev der truffet følgende beslutninger vedrørende prioritering af ID15-oplande til implementering af N-MAP-konceptet:

- Jo højere heterogenitet i undergrunden med hensyn til geologi og redoxforhold, desto højere prioritet.

For det andet blev det besluttet at bruge en binær tilgang til følgende forhold:

- En høj grad af N-retention i overfladevandssystemet betyder, at områderne udelukkes.
- En høj grad af N-tilstrømning direkte til dræn og grøfter fra landbrugsmarkerne betyder, at disse arealer udelukkes.
- Alle områder med N-reduktionskrav er inkluderet, mens områder uden krav er undtaget.

Prioriteringsværktøjet implementeres gennem en tretrins, hierarkisk sammensat indikatortilgang ved hjælp af det udskudte N-reduktionskrav fra Vandplan (VPII) og scoring af fem udvalgte temaer omhandlende: 1) geologisk kompleksitet og 2) redoxkompleksitet, kombineret i trin 1, 3) N-retention i overfladevand og 4) dræningsgrad kombineret i trin 2, og 5) N-reduktionskrav i trin 3. Denne hierarkiske tilgang blev valgt, fordi den er fleksibel og giver mulighed for trinvise ændringer. For eksempel vil det være muligt at revidere trin 3, når N-reduktionskravet for målrettet N-regulering i VPIII er kendt.

De otte undersøgelsesområder fra rOPEN (Javngyde og Sillerup) og MapField (LOOP 2, 3, 4 og 6 samt de to demo-sites ved Salling) er brugt til at demonstrere prioriteringsværktøjets performance i henhold til de fem temaer. Hvert af de otte undersøgelsesområder består af 1-3 ID15-oplande. Javngyde har den højeste score af alle otte undersøgelsesområder med en samlet score på 0,8 på grund af høj geologisk og redox-kompleksitet, og Sillerup har den laveste total-score på nul på grund af høj grad af N-transport i dræn. LOOP 2, der ligger i Himmerland, har en lav total-score på 0,2 på grund af en relativt lav redox-kompleksitet. LOOP 3 ved Ejer Bavnehøj har også den laveste total-score på nul i ca. 45 % af arealet på grund af en høj andel af N-transport i dræn i to af ID15-oplandene i dette område. De resterende 55 % af undersøgelsesområdet har en samlet score på 0,48 på grund af middelhøj score i geologisk kompleksitet (score T1 0,8) og medium redox-kompleksitet (score T2 = 0,6). LOOP 4 ved Lillebæk på Fyn har samlet score fra 0-0,48 på grund af forskellig grad af dræning og redox-kompleksitet. LOOP 6 ved Bolbro i Syddanmark har total-score fra 0-0,64 på grund af forskellig grad af geologisk og redox-kompleksitet samt dræning i området.

Det udviklede prioriteringsværktøj har fokus på overfladevand og beskyttelse af kystområder. Et lignende prioriteringsværktøj, der alene fokuserer på grundvandsbeskyttelse, kan udvikles baseret på en tilsvarende sammensat indeksmetode, hvor relevante temaer for grundvandsbeskyttelse inkluderes.

Den højopløselige kortlægning og modellering med N-MAP-konceptet i de otte undersøgelsesområder i projekterne rOPEN og MapField afslørede højere kompleksitet af undergrunden end tidligere kendt. Derfor er der begrænsninger i brug af eksisterende data til evaluering af den lokale kompleksitet, som indgår i det udviklede prioriteringsværktøj.

Usikkerheder og begrænsninger relateret til de udvalgte fem temaer diskuteres i denne rapport, og alle temaer er foreløbige i den forstand, at temaerne med tiden bør opdateres, når ny viden dukker op. Især viser erfaringerne fra MapField, at redox-kompleksitet og -arkitektur ikke er den eneste vigtige geokemiske parameter til at vurdere N-retentionen i undergrunden. N-reduktionsraten er også meget vigtig, men denne parameter kan ikke tages i betragtning i prioriteringsværktøjet på nationalt plan på grund af for få målinger til generalisering på nationalt niveau indtil videre.

2 Introduction

This report is initiated in the context of the Innovation Fund Denmark project MapField.

In 2013, the Commission of Nature and Agriculture (Natur- og Landbrugskommissionen) recommended a new Danish paradigm with a shift from national to targeted nitrogen (N) regulation to benefit both production and the environment. In 2016, the Danish Government started introducing a more targeted N-regulation with implementation of the Food and Agricultural package from 2015. The vision of targeted N-regulation was later expressed in the political agreement from 2018 (Miljø- og Fødevareministeriet, 2018), and the political agreement by the Danish Government in June 2019 (The Danish Government, 2019). In October 2021, the Danish Government and a majority of the other political parties agreed on a green transition of Danish agriculture, including an annual reduction of 6500 tons N in the coastal catchments by means of targeted N-regulation in the agricultural fields (The Danish Government, 2021).

A new concept (called N-MAP) and new technologies have been developed through the Innovation Fund Denmark projects rOPEN and MapField (http://mapfield.dk/) to form the basis for targeted N-regulation at field level based on detailed mapping of the subsurface geological and redox structures (rOPEN & MapField, 2021). The aim is to ensure an environmentally and economically sustainable development of the Danish agricultural food production that meets the demands of the EU's environmental directives.

The purpose of this report is to describe a prioritization tool, which can assist in selecting the areas that are most suitable for implementing the N-MAP concept to support targeted N-regulation of agriculture to harvest the largest possible benefits for both the environment and the agricultural production.

2.1 N-retention in the landscape

N-retention describes the amount of nitrate, which leaches from the field, and which does not reach the surface waters because of natural turnover or denitrification in different parts of the landscape and subsurface. At the catchment scale, N-retention includes denitrification in A) the groundwater zone (incl. the drainage), B) the unsaturated zone (incl. the root zone), C) the riparian zone, and D) the surface water system (***Figure 1***).

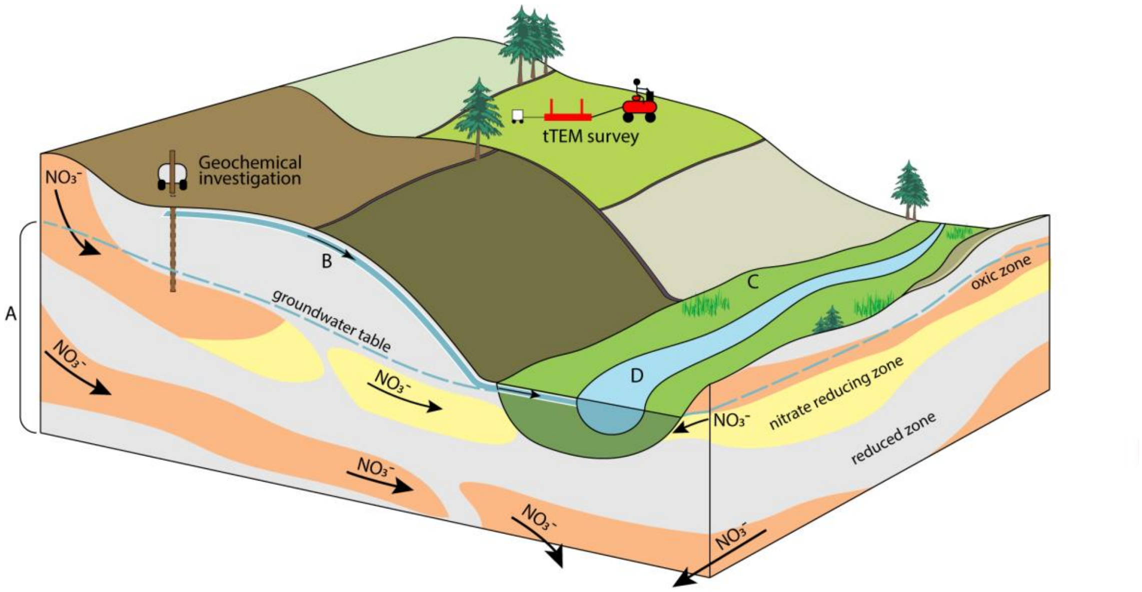

Figure 1 *Conceptual drawing of the important N-retention sources and processes in the landscape and subsurface. A: the groundwater zone, incl. the drainage, B: the unsaturated zone, incl. root zone, C: the riparian zone and D: the surface water system.*

The N-MAP concept focuses on the groundwater N-retention in the subsurface. It is developed to form the basis for a precise and targeted regulation of the agricultural use of N at field level. At field level, the actions and mitigation measures can be adapted to the N-turnover in the subsurface right under each field. The adaptation to field level is meant to secure that the effect is as high as possible regarding cost-efficiency of N-reductions in the aquatic environment.

2.2 The N-MAP concept

The N-MAP concept is based on the collection, interpretation, and modelling of large amounts of data to precisely calculate the transport and turnover of water and N in the subsurface. The result is a high-resolution map of the N-retention in the subsurface, e.g. at field level with a relatively low uncertainty.

The N-MAP concept for the production of N-retention maps at field level consists of five steps and is adapted for ID15 catchment areas (approx. 1500 hectares) as shown in ***Figure 2***. It is flexible in the sense that catchment areas can be prioritized in different ways, e.g. depending on specific demands regarding reduction of N or uncertainties in the existing knowledge base. The concept makes it possible to only complete Step 1 or Step 2 in a catchment area, if for example it turns out not to be cost-efficient to continue. In other catchment areas, it might be necessary to complete all five steps.

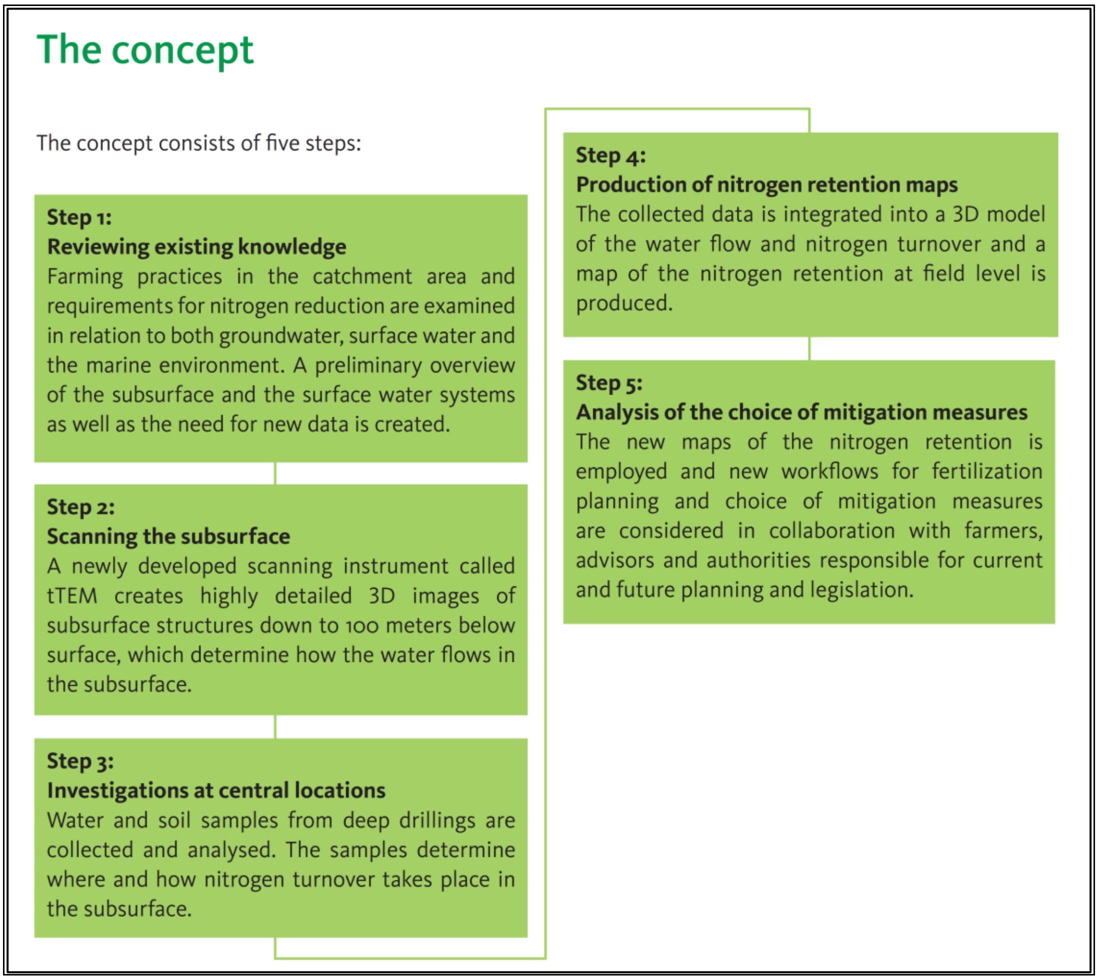

Figure 2 *The five steps in the N-MAP concept (https://eng.mapfield.dk/).*

The production of the N-retention maps takes place in Step 4. It consists of five elements:

- **3D model of subsurface structures.** The model shows the distribution of different geological layers in the subsurface. In focus is to what extend the different layers can transport water and whether they are connected.
- **3D model of N-turnover.** The model shows the distribution of the different zones in the subsurface with regards to where and how fast N is removed in the different zones.
- **N-leaching from the root zone.** The N-leaching is estimated for each field for each year. The emphasis is on the type of crops on the fields and the total amount of fertilizers applied to each field.
- **3D flow model.** The model calculates how much, how fast, and in which direction the water flows through the subsurface. The focus is on the model’s ability to

predict the water flow in streams and drains as well as measured water levels in boreholes.

- **N-retention maps.** Estimation of the N-retention is done with a 3D flow and N-retention model, which simulates the amount of N that is emitted to streams compared to what has leached from the root zone. The agreement between simulations and measurements of the actual N-transport in the streams is considered.

2.3 Structure of the report

This report describes a prioritization tool which can assist in selecting, which ID15 catchments and areas are most suitable for implementing the N-MAP concept to support targeted N-regulation of agriculture.

In the report, the selected approach and themes are described in chapter 3, and in chapter 4 the scoring of the themes and the final prioritization tool and map are presented for selection of ID15 catchments within coastal catchments. Chapter 5 covers a demonstration of what the prioritization looks like in the eight case studies of rOPEN and MapField, and chapter 6 includes a discussion of the prioritization tool in regard to uncertainties, limitations, flexibility and possibilities for further prioritization in step one of the N-MAP concept, and prioritization regarding groundwater protection is also discussed.

3 The selected approach including themes

The development of the prioritization tool has been discussed at several workshops in 2020-2021 with internal and external experts (contributing authors of this report).

The following decisions were made:

1. The purpose of this report is to develop a prioritization tool for implementing the N-MAP concept in the targeted regulation of agricultural fields in Denmark.

2. The prioritization tool should be able to produce a national map showing a prioritized order of the hydrological ID15 catchments of about 15 km^2.

3. The tool should be developed in a GIS environment as a composite index of selected themes.

4. The development of the GIS prioritization tool should take into consideration the natural geological, hydrological, hydrogeological, and geochemical conditions of the landscape and subsurface.

5. The final prioritization map should include the requirements for N-reduction in the coastal catchments according to the implementation of the Water Framework Directive, WFD (EC, 2000) in the River Basin Management Plan II (VPII) or III (VPIII), if available.

6. The final prioritization map should be able to support the national plans of reaching the WFD targets.

3.1 The ID15 catchment level

The ID15 catchments were selected as the smallest target units (***Figure 3***). This is because it is currently the smallest level of targeted N-regulation of agriculture in Denmark, and the level at which the current legislative national N-retention maps are produced. All input data for the prioritization tool are aggregated to the ID15 catchment scale, so each catchment can be described by a single value for each of the selected themes.

The same version of the map of ID15 catchments is used as in the national N-retention map from 2020 in Højberg et al. (2021). The average area is 12.8 km^2 and the total number of ID15 catchments is 3351, which includes more than 200 new catchments compared to the previous map. In ***Figure 3***, the ID15 catchments are divided into 5 equally sized groups showing that 20% of the catchments are smaller than 3.4 km^2 and 20% are larger than 22.7 km^2.

Figure 3 also shows the eight study sites from the rOPEN and MapField projects, located in Jutland and Funen, used in the demonstration of the prioritization tool.

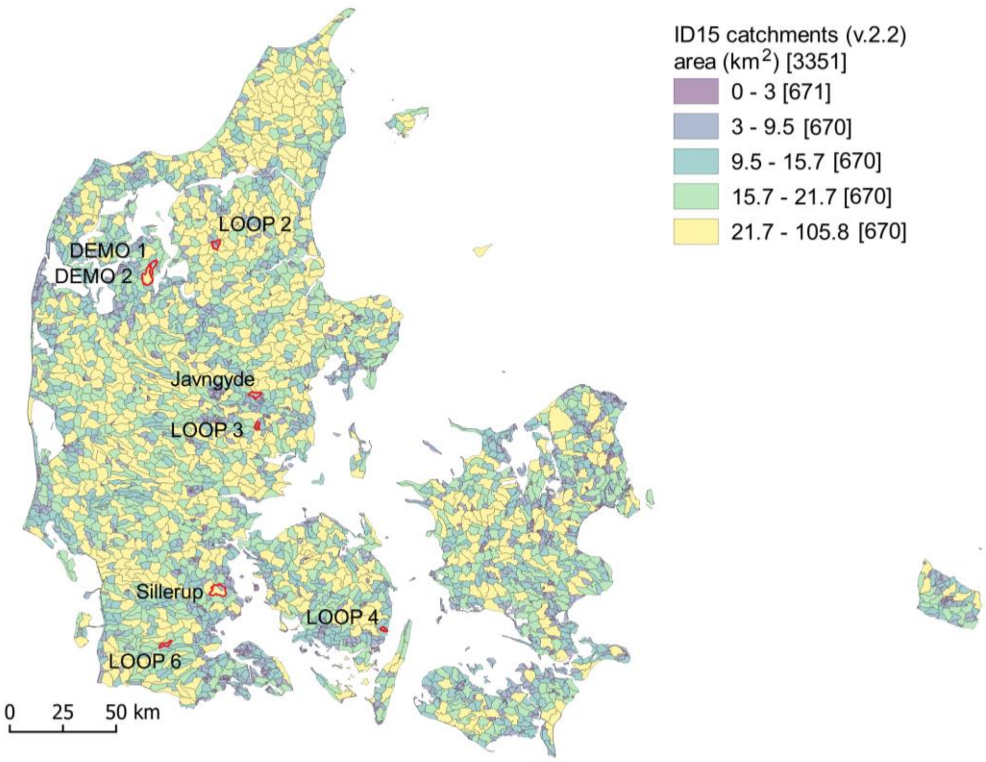

Figure 3 *Map showing the ID15 catchments (Højberg, 2021) classified by area and the eight study sites in the rOPEN and MapField projects used to discuss the prioritization tool (red); the number of catchments in each category is shown in the square brackets.*

3.2 Approach and selection of themes

There needs to be variation in the N-retention between fields within the administrative ID15 catchment before it is viable to implement targeted regulation of the N-fertilization and management at field scale. Therefore, the question is:

Which areas are most suitable for implementing the N-MAP concept to support cost-efficient targeted regulation of agriculture for protection of the coastal areas?

The tool is developed through an iterative process with internal and external experts in workshops and individual meetings, eliciting knowledge on specific issues, and finally, based on the experts' comments on the first version of this report.

The following decisions were made regarding the prioritization of the ID15 catchments for implementation of the N-MAP concept based on the above-described collaboration. The aim of the collaborative process is to reach a consensus, or an optimal compromise, as evaluated by the editors.

The first prioritization is based on the natural geological, hydrogeological, hydrological, and geochemical conditions:

- **The higher the heterogeneity in the subsurface geology and redox conditions, the higher the priority**. This is due to a relatively high variation in the water pathways and nitrate reduction in the subsurface, and thus variation in the groundwater N-retention, and the need for detailed data is expected to be large within the ID15 catchment.

Secondly, it was decided to use a binary approach regarding the following conditions:

- **A high degree of N-retention in the surface water system means that the areas are excluded**. This is because a major part of the N-retention occurs in the downstream surface waters and lakes, and therefore groundwater N-retention in the ID15 catchment becomes less important. That means that only areas where groundwater N-retention is a considerable part of the total N-retention to the coastal areas are included.
- **A high degree of N-flow directly to drains and ditches from the agricultural fields means that these areas are excluded**. This is because when a major part of the water and N flows via drains towards the streams, the groundwater N-retention becomes less important. It means that only areas, where the groundwater N-retention in an ID15 catchment is a considerable part of the total N-retention to the outlet from the ID15 catchment, are included. This way, areas with mixed groundwater flow and drain flow are included because these are potential areas for implementation of the N-MAP concept.
- **All areas with N-reduction demands are included, while areas with no demands are excluded.** This map can be changed when new N-reduction demands are agreed on.

Therefore, it is decided to include the following five themes in the prioritization tool:

- Theme 1: Geological complexity (Geology)
- Theme 2: Redox complexity (Redox)
- Theme 3: N-retention in surface waters (Surface water N-retention)
- Theme 4: Degree of drainage (Drains)
- Theme 5: N-reduction demand (Demand)

The selection of the most appropriate data sources and their processing is discussed and revised during the workshops and the individual meetings with the relevant experts.

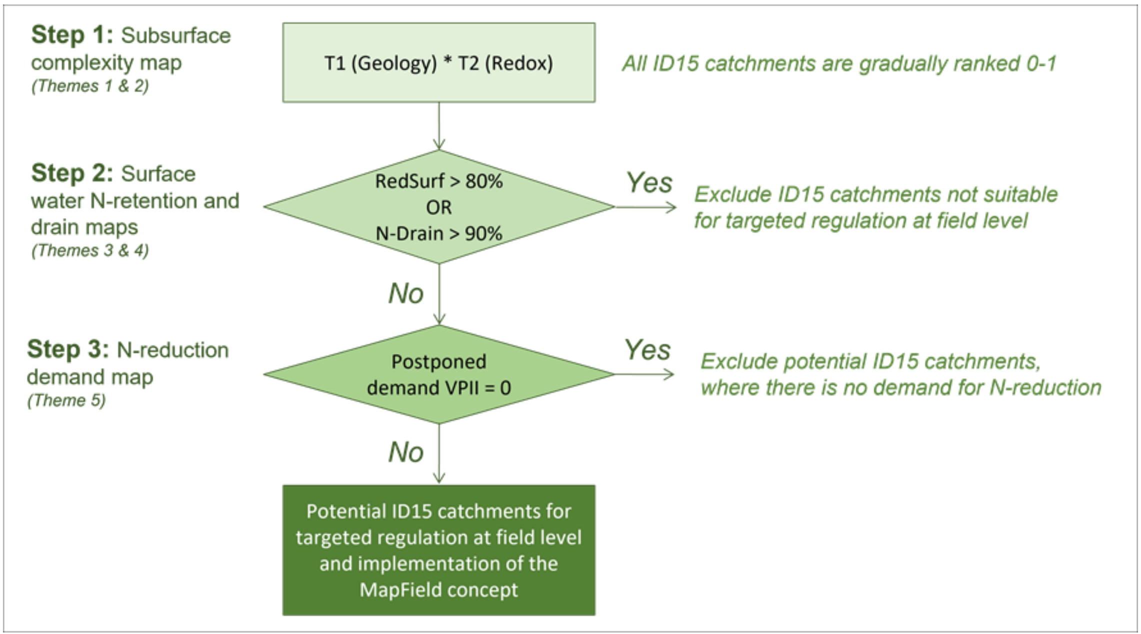

Figure 4 *A flowchart showing how the five themes are used together in the MapField prioritization tool to derive a map with potential ID15 catchments for targeted regulation at field level and for implementation of the N-MAP concept.*

The prioritization tool is implemented through a three-step, hierarchical approach (**Figure 4**):**Fejl! Henvisningskilde ikke fundet.**

- **Step 1** (Subsurface complexity map) combines the rated maps from Theme 1 (Geology) and Theme 2 (Redox) by multiplying them. As a result, all ID15 catchments receive a gradual ranking from 0 to 1 where 1 is expressing the highest priority.
- **Step 2** uses Theme 3 (Surface water N-retention) and Theme 4 (Drains) to exclude the ID15 catchments where surface water N-retention exceeds 80%, or the fraction of N-transport through drains and ditches exceeds 90%.
- **Step 3** (N-reduction demand, Theme 5) consists of excluding the ID15 catchments where there is no demand for N-reduction.

This hierarchical approach was selected because it is flexible and allows for stepwise changes. For example, when the N-reduction demand for VPIII is known, only Step 3 would need to be revised.

3.3 Theme 1: Geological complexity

A high geological complexity within an ID15 catchment is expected to give a high variation in the water flow paths. This is anticipated to give a high variation in the N-retention maps within an ID15 catchment, and thereby potential for a differentiated N-regulation on the fields.

A map of the geological complexity is developed for the purpose of this prioritization tool (Sandersen, 2021). The concept of the map is explained in detail in Sandersen (2021), but the main idea is that Denmark can be sub-divided in areas of different geological complexity based on landscape types in the upper 30 m of the subsurface.

Figure 5 shows a sketch of the different landscape types, while ***Table 1*** shows the complexity of each landscape type.

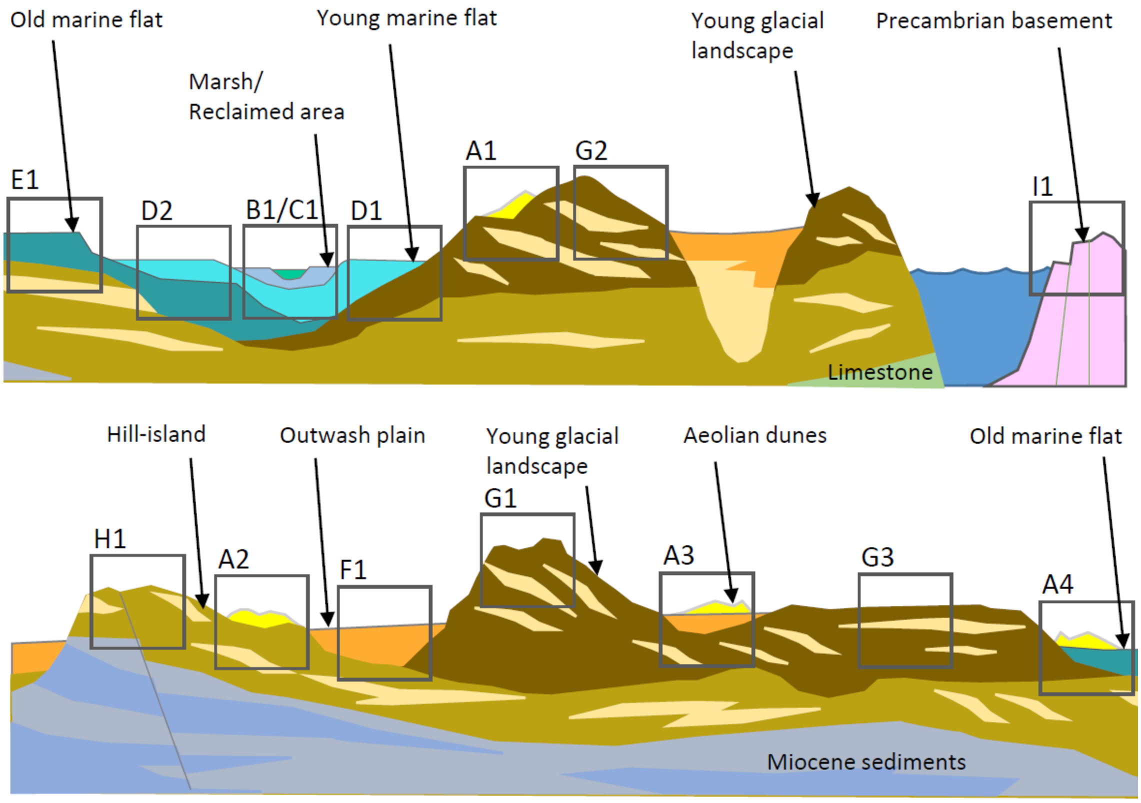

Figure 5 *Sketch of the landscape types included in the classification (Sandersen, 2021).*

Table 1 *Classification of the landscape types (Sandersen, 2021); abbreviations: L – low complexity, LM – low to moderate complexity, MH – moderate to high complexity, H – high complexity.*

Unit	Sub-unit	Landscape type	Complexity
A	1	Aeolian dune on young glacial landscape	MH
	2	Aeolian dune on hill island	MH
	3	Aeolian dune on outwash plain	L
	4	Aeolian dune on Late- or Postglacial marine flat	L
B	1	Reclaimed area (former lake or marine fiord)	LM
C	1	Marsh on older flats (marine/non-marine)	LM
D	1	Young marine flat (Littorina) on older sediments (glacial/non-glacial)	LM
	2	Young marine flat (Littorina) on older marine flat (Yoldia)	L
E	1	Old marine flat (Yoldia) on older sediments	LM
F	1	Outwash plain on older sediments	LM
G	1	Young glacial landscape, ice-margins, on older landscape/sediments	H
	2	Young glacial landscape, hilly, on older landscape/sediments	MH
	3	Young glacial landscape, smooth, on older landscape/sediments	LM
H	1	Old glacial landscape (hill island) on older landscape/sediments	MH
I	1	Precambrian basement	L

All landscape types were provided as different layers. To use the map here, first we dissolved all 15 layers to 4 layers that had the same geological complexity: low (L), low to moderate (LM), moderate to high (MH), and high (H). This way, all areas were assigned to one of the four complexity classes. Then, using the QGIS tool “Overlap analysis”, we calculated the percentage of each ID15 catchment covered by each of the four complexity types (L, LM, MH, H). Each ID15 catchment was then classified in one of the four classes, based on the highest complexity class that had at least 10% coverage within the catchment (***Figure 6***).

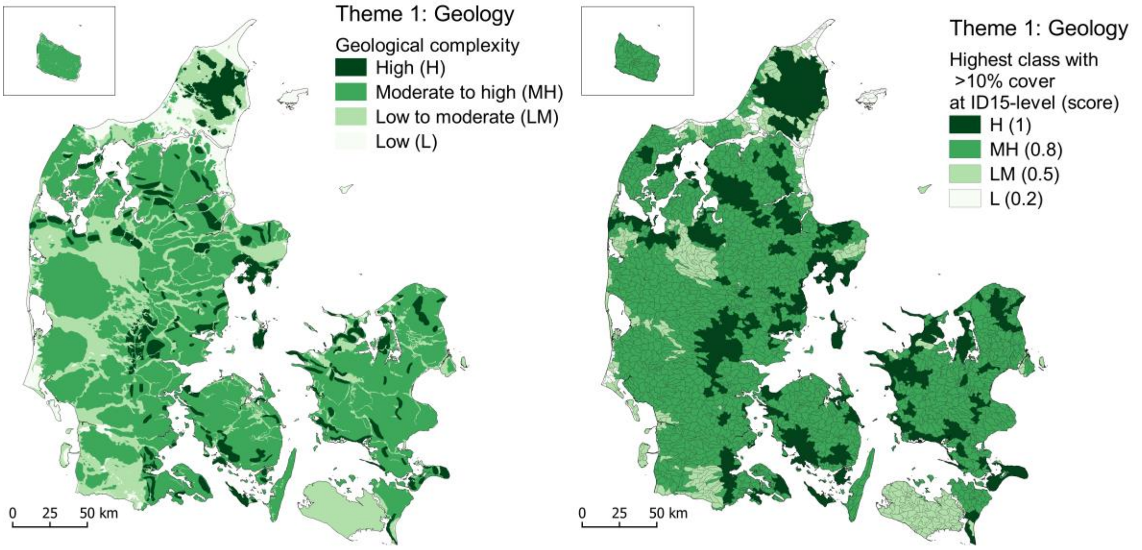

Figure 6 *left: Geological complexity map (Sandersen, 2021); right: ID15 catchments classified by the highest complexity class with more than 10% area coverage.*

The idea was to take the highest complexity class for each ID15 catchment, while accounting for possible uncertainties stemming from the development of the geological complexity map (or the input data used for it). Thus, the highest class had to cover more than 10% of the ID15 catchment to be considered, as 10% was used as an uncertainty threshold.

The scoring of Theme 1 shown in ***Figure 6*** was evaluated based on the analysis presented in the report by Sandersen (2021). The low geological complexity (L) was assigned a very low score (0.2) and the low to moderate complexity (LM) a medium score (0.5). The moderate to high (MH), and high (H) complexity groups were given high and very high scores of 0.8 and 1, respectively, because these are the areas showing high geological complexity.

3.4 Theme 2: Redox complexity

A high redox complexity within a catchment indicates a high variation in the water flow paths and in the nitrate reduction in the subsurface. Firstly, this is anticipated to give a high variation in the N-retention maps between fields within the ID15 catchment, and thereby the potential for a differentiated N-regulation on the fields. Secondly, high redox complexity must be addressed by detailed investigations by implementing the N-MAP concept to reduce uncertainties in the N-retention maps.

The complexity of the redox structures is analysed by comparing the depth of the nitrate-containing groundwater and the depth of the national first redox interface (FRI) from Koch et al. (2019). When the nitrate-containing water is found below the FRI, it is an indication of complex water flow paths and complex nitrate reduction in underlying geological layers below the FRI. Agreement between the FRI and the depth of the nitrate-containing groundwater, indicates low redox complexity and a low priority for implementation of the N-MAP concept because of indications of low variation in the N-retention maps between the fields, and because flow paths and subsurface N-reduction can be investigated with the already existing data sources. On the other hand, the larger the difference between the two, the stronger indication of redox complexity, and therefore a higher priority for implementing the N-MAP concept. If there are complex redox conditions, there is a potential for differentiated N-regulation between the fields, and at the same time there is a need for obtaining more detailed knowledge about redox conditions for reduction of uncertainties in the N-retention maps.

The data sources for Theme 2 include (1) the national FRI map (Koch et al., 2019) and (2) a map showing the depth of nitrate-containing groundwater (***Figure 7***).

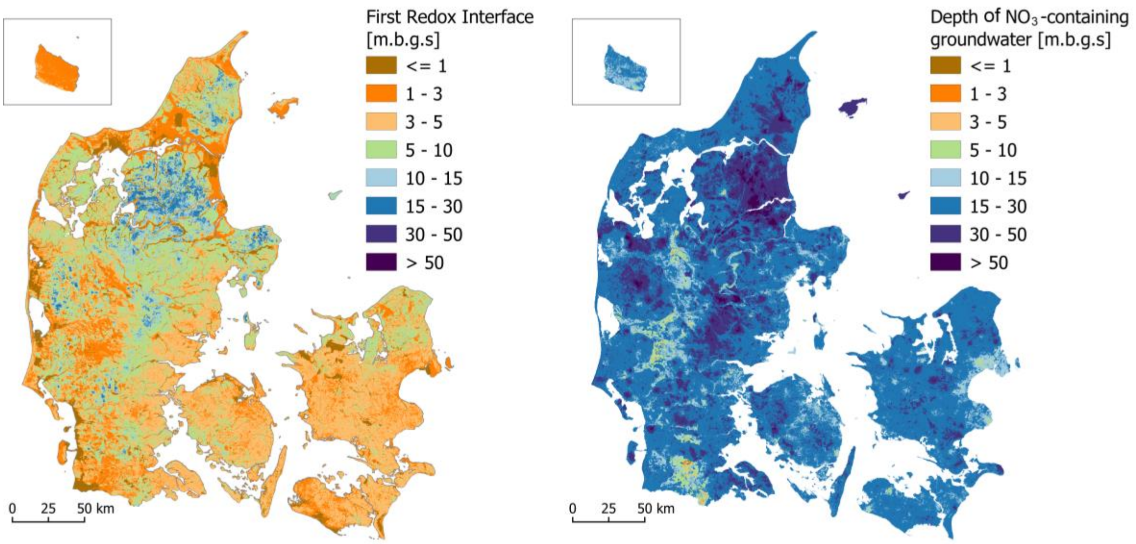

Figure 7 *Input data for Theme 2: First redox interface (Koch et al., 2019) and modelled depth of nitrate-containing groundwater (top intake, only A and B redox water types); m.b.g.s. is meters below ground surface.*

The map with the depth of nitrate-containing groundwater was obtained by applying the same machine learning modelling approach as used for the FRI map, but on the depth of well-screens containing nitrate. This depth is based on the top of the deepest well-screen containing NO_3 > 1 mg/l and classified as A or B redox water type (see details in Appendix 1).

The modelling was done in two steps:

(1) Random Forest (RF) models were trained using the well data and 18 covariates. The training datasets contained 15,601 wells for the first redox interface (FRI map) and 3,167 wells for modelling the redox status based on the depth of nitrate-containing

groundwater (AB map). The 18 covariates comprise national maps, resampled to 100 m, reflecting the geological, hydrological, and topographical variability (see Appendix 1, ***Table*** 7). After training, the two models were used to predict the variables at a spatial resolution of 100 m.

(2) For the FRI map, two geostatistical models (hill islands area and the rest of the country) of the RF residuals were built by fitting a variogram model that was subsequently applied in a Kriging interpolation. For the depth of nitrate-containing groundwater map (AB map), a single geostatistical model covering the whole of Denmark was built to interpolate the RF residuals.

Finally, the interpolated residuals were added to the RF prediction. This method is referred to as Random Forest Regression Kriging.

The variable importance has been calculated for both models (FRI and AB) and is illustrated in Appendix 1 (***Figure 20)***. This parameter quantifies the importance of each of the 18 covariates and is useful to interpret the trained RF models.

To derive the map for Theme 2, the two raster maps from **Figure 7** were subtracted (FRI – AB depth) and then the median depth difference for each ID15 catchment was calculated (***Figure 8***).

The scoring of Theme 2 (Redox) shown in ***Figure 8*** was evaluated within the contributing author group, and it was decided to use a scoring that gradually increases with increase in the depth-difference. The lowest score (0.2) was given to the ID15 catchments, where the difference between the first redox interface and the depth to nitrate-containing groundwater was less than 5 m, while the highest score (1) was given to the ID15 catchments, where the difference was larger than 23 m.

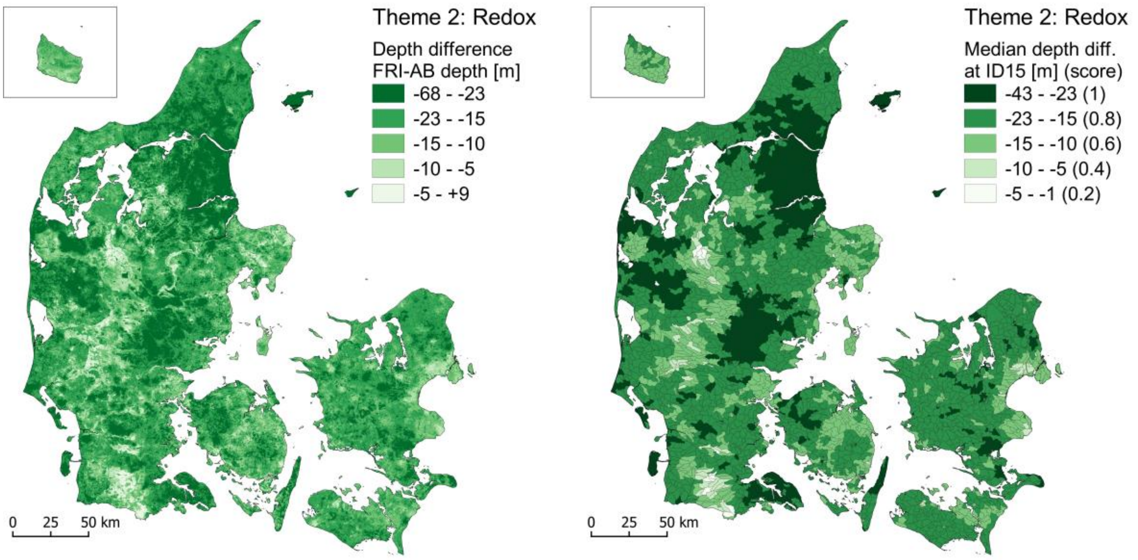

Figure 8 *Depth difference between the first redox interface (FRI) and the depth to nitrate-containing groundwater (AB) (left); median of the depth difference at ID15 catchment in meters (right) (the scores used in the tool are provided in parenthesis).*

3.5 Theme 3: N-retention in surface waters

The N-MAP concept focuses on determining the N-retention in the groundwater within an ID15 catchment. Therefore N-retention in the surface water system within an ID15 catchment is not (so far) determined by the N-MAP concept.

In the prioritization tool, it was decided to exclude ID15 catchments with surface water N-retention exceeding 80%, and the rest of the catchments were retained in the prioritization process. This resulted in the exclusion of 135 ID15 catchments with a total area of 66,791 ha. These are mainly ID15 catchments part of coastal catchments containing major lakes.

The argument for the threshold value of 80% is that a high degree of N-retention in surface waters of the total N-retention to the marine areas indicates that a major part of the N-retention occurs in downstream surface waters and lakes. Therefore, the groundwater N-retention in the ID15 catchment becomes less important. This means that areas where the groundwater N-retention is a considerable part of the total N-retention (> 20%) to the marine areas are prioritized because of their potential for targeted N-regulation at field level within the ID15 catchment. This value (80%) was agreed upon by the experts in the project.

The degree of N-retention in surface waters is a directly extracted from the national N-model (Højberg et al., 2021), were the N-retention of surface waters (RedSurf) is calculated for each ID15 catchment. RedSurf accounts for all reduction in the surface waters within the ID15 catchment and all the way downstream until it reaches the coast (***Figure 9***).

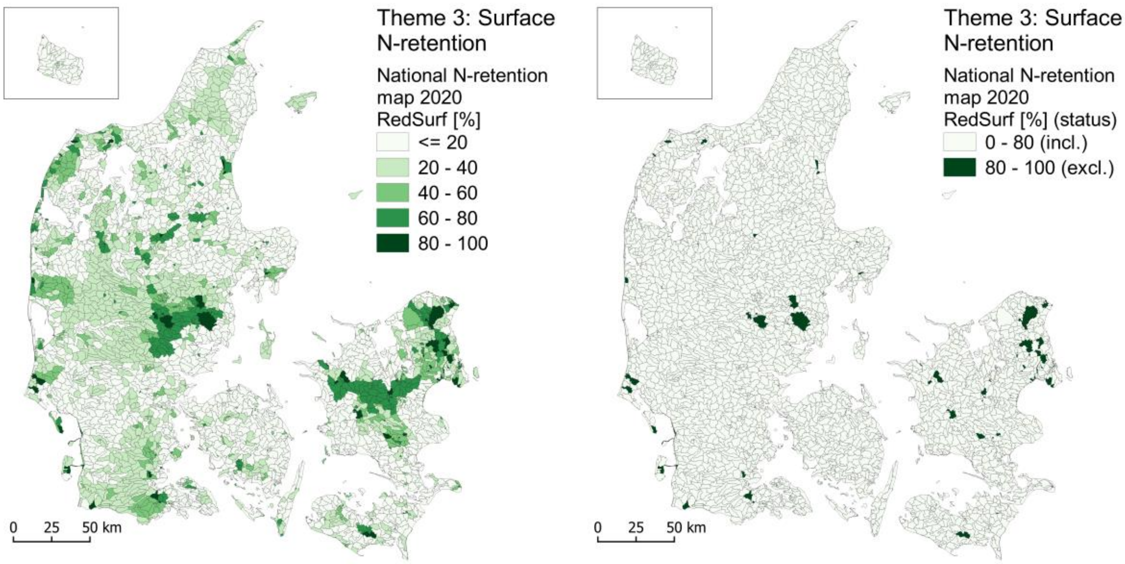

Figure 9 *Surface water N-retention from the national N-model (left) (Højberg et al., 2021) and indication of which ID15 catchments are excluded or included in the prioritization tool (right).*

3.6 Theme 4: Degree of drainage

In the prioritization tool, it was decided to exclude the ID15 catchments where the N-transport through the drains and ditches exceeded 90%. This resulted in the exclusion of 1224 ID15 catchments with a total area of 1,315,560 ha. These are mainly areas located around the coastlines, in lowland areas, and in the clay-rich parts of Lolland, Zealand and Funen.

The argument for the threshold value of 90% is that a high degree of drainage, as seen on the systematically drained areas with a homogeneous near-surface clay layer, means that a major part of the water and N flows directly via drains towards the streams. In this situation the groundwater N-retention becomes less important. This is also the case with ditches and other near-surface water flow paths in lowland areas. This value (90%) was agreed upon by the experts in the project. On the other hand, when there is a mixture of groundwater flow and drainage flow within the ID15 catchment, or groundwater flow is the major part, then the ID15 catchment is prioritized for implementing the N-MAP concept. Implementing the N-MAP concept will provide us with more knowledge about the subsurface conditions to reduce uncertainties in the N-retention maps.

It was discussed, which map to use for Theme 4 on degree of drainage, and different options were considered. The probability map for drained areas from Møller et al. (2018) was considered, but this map does not give any information about the flow in the drains. Another option was the simulated drain flow from the DK-model (Højberg et al., 2021), but these estimations only considered water flow, not N-transport. Finally, it was decided to use the simulated fraction of N-transport through drains and ditches from the national N-model (Højberg et al., 2021), because it shows exactly what we are looking for, namely the flow of N in drains. The fraction of N-transport through the drains (and ditches), N_DrnFrac, is defined as the mass of N that flows directly through the drains (and ditches) to the surface waters divided by the total mass of N that reaches the surface waters calculated on ID15 catchment scale (***Figure 10***).

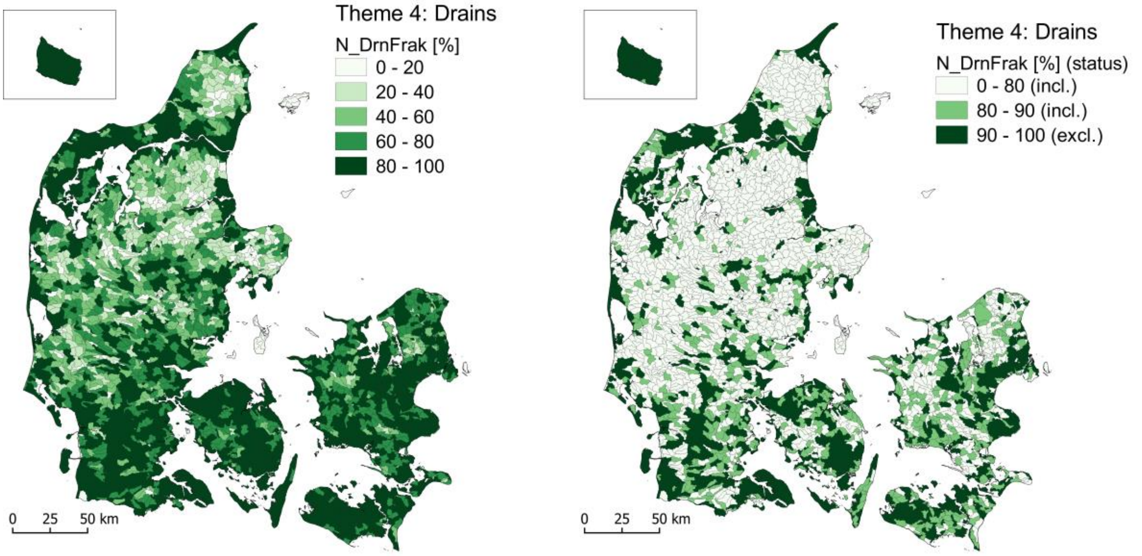

Figure 10 *Fraction of N-transport through drains and ditches (N_DrnFrak) at the ID15 catchment scale from the national N-model (Højberg et al., 2021); left – five classes, right – three classes and an indication of which ID15 catchments are excluded or included in the prioritization tool.*

3.7 Theme 5: N-reduction demand

In Theme 5, the N-reduction requirements for the coastal catchments (n=90) from VPII are used. When the N-reduction requirements change, e.g. with VPIII, this theme can be revised.

The following data sources are used for this theme:

1) The postponed N-reduction requirement (dk: *Udskudt indsats, efter 2021*) in tons N per year, provided in Appendix 1 of the River Basin Management Plan II report (Miljø- og Fødevareministeriet, 2016).
2) The polygon shapefile "vp2_2016nbel12_deloplande" including the 90 coastal catchments, downloaded from MiljøGIS (https://mst.dk/service/miljoegis/hent-data/).

The values from 1) are manually written into the shape file from 2) (***Figure 11***).

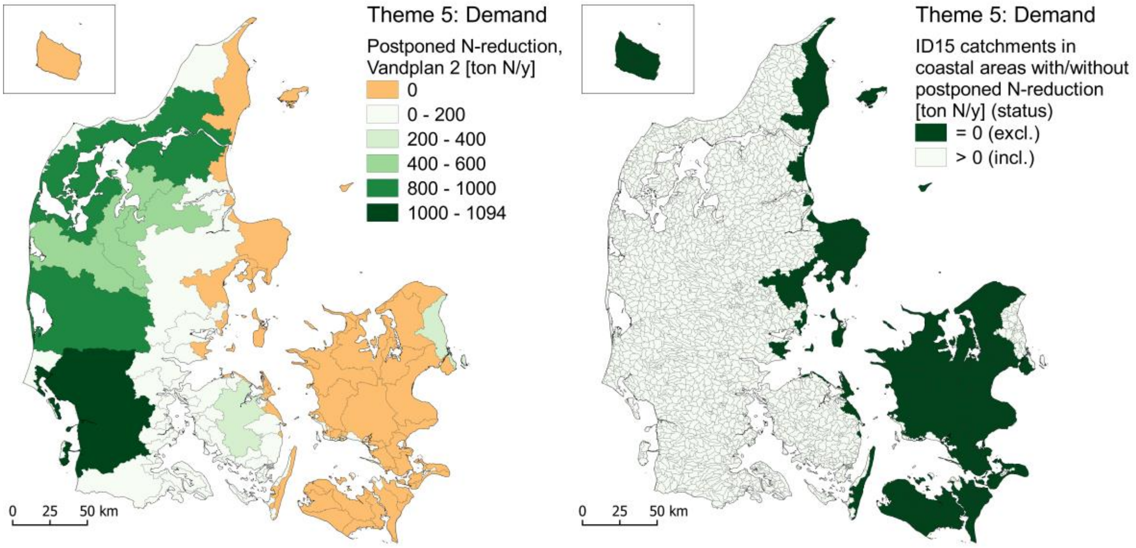

Figure 11 *Postponed N-reduction requirement from VPII at the 90 coastal catchments (left) and the ID15 catchments in these areas with/without postponed N-reduction requirements (right)*

The ID15 catchments that are in the coastal catchments without N-reduction demand, based on the postponed N-reduction from VPII (=0 t N/y) (***Figure 11***) are excluded from the final prioritization map. The rest of the ID15 catchments are retained. This resulted in the exclusion of 1123 ID15 catchments with a total area of 1,291,648 ha.

4 The development of the prioritization tool

4.1 Composite indicators

The prioritization tool is developed as a composite indicator. Composite indicators (or indices) are formed by compiling individual indicators in a combined single index, reflecting a complex multidimensional system (Greko et al., 2019). Their potential advantage is that the results are presented as scores or rankings that key stakeholders, decision makers, and the public can easily comprehend (USAID, 2014). The final prioritization map combines the five themes in the 3-step hierarchical approach, described in section 3.2 (see ***Figure 4***).

The derivation of the final prioritization map can be represented by the following equation:

$$Prioritization\ tool = \prod_{i=1}^{5} T_i = (T_1 * T_2)_{step\ 1} * (T_3 * T_4)_{step\ 2} * (T_5)_{step\ 3}$$

where T_i are the five rated thematic maps and i is an index for each of them. In this multiplication, the maps from themes 3-5 are presented in a binary way, where the ID15 catchments to include/exclude are given 1/0 values, respectively, while the maps from themes 1 and 2 are rated gradually in the range 0-1. The multiplication procedure is carried out in a GIS environment (QGIS v. 3.10) in the described 3 steps.

This method falls under the geometric aggregation of composite indicators (i.e. multiplicative combination), within the wider research field dealing with multi-criteria decision analysis (Greko et al., 2019). Generally, geometric aggregation is used because it avoids concerns related to compensability and interaction, which are an issue with linear aggregations using the sum of weighted/unweighted indicators (Greco et al., 2019; USAID, 2014).

Using multiplication in the prioritization tool means that if an ID15 catchment has a low score for one of the themes, it will end up with a low priority score in the final map. Thus, it is not possible to compensate the low score within one thematic map with a high score in another. ID15 catchments having a high score in the final prioritization map are those with high scores for all five thematic maps. Scores on the final map higher than 0.6 (result of 0.8×0.8=0.64) can be regarded as high as these rely on both a geological complexity score and a redox complexity score higher than 0.8.

This is especially relevant for the subsurface complexity map (Step 1), where the ID15 catchments with the highest rank/score (1) will be those, which had the highest score for both Theme 1 (Geology) and Theme 2 (Redox). On the other hand, if an ID15 catchment had a low score in even one of these two themes, it would result in a low score at Step 1. In the other two multiplication steps, based on the maps from themes 3-5, the ID15 catchments with score 0 are excluded from the final prioritization map irrespective of their rank/score from Step 1, while the rest of the ID15 catchments would keep their score from Step 1.

The scoring system is developed by keeping in mind that a multiplicative combination method will be used and that no weights will be assigned to the themes. Thus, it was decided that the chosen scoring system of each of the five themes should incorporate the relative importance of each theme.

4.2 Overview of the rated themes

The percentage of ID15 catchments in each class for each of the five themes and their corresponding areas are presented in ***Figure 12*****,** and the absolute numbers are seen in ***Table 2***. The geographical distribution of each of the five themes are shown in ***Figure 13***.

The highest score (1) for Theme 1 (Geology) and Theme 2 (Redox) are given for 21.3% and 20.4% of all the ID15 catchments, respectively (***Figure 12***). This corresponds to 23.6% and 19.9% of the area of Denmark. Regarding Themes 3-5, 96.0%, 63.5%, 66.5% of all ID15 catchments are given score 1, which results in 98.4%, 69.5%, and 70%, of the area, respectively.

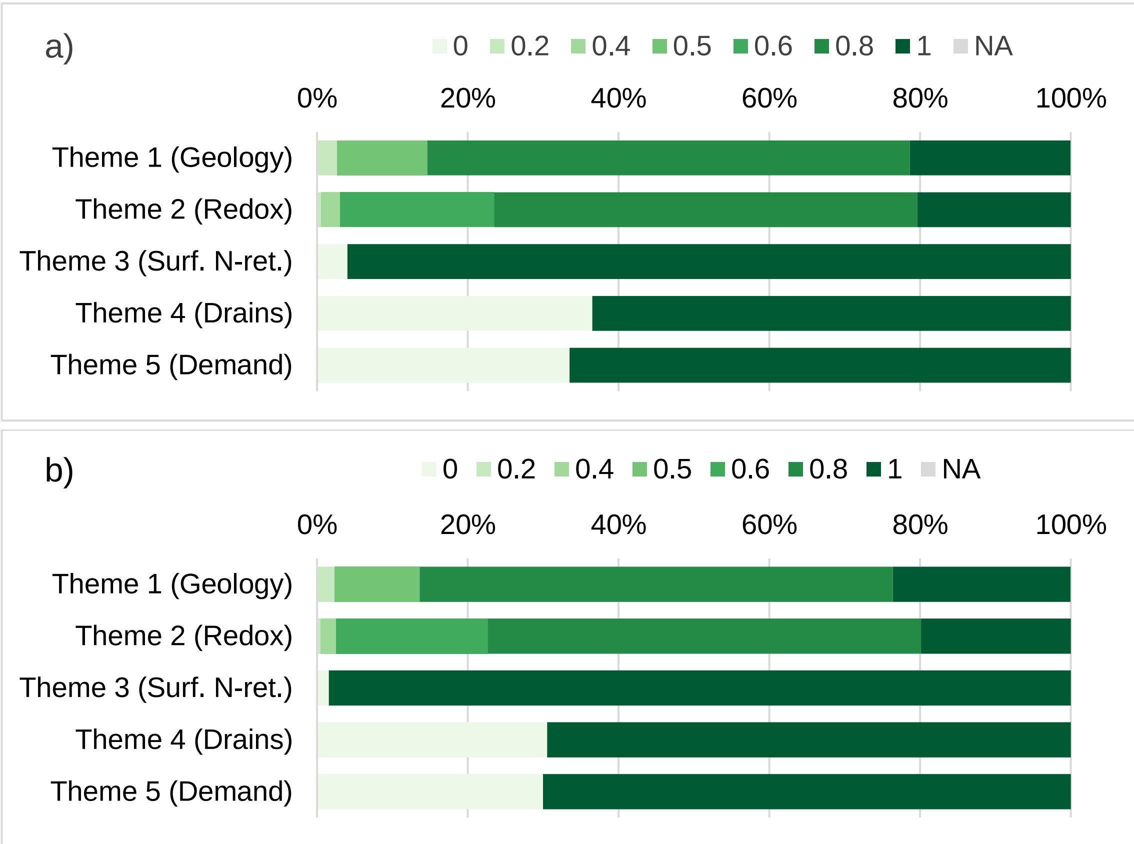

Figure 12 *a) The percentage of the ID15 catchments of all 3351 in each score class for each theme; b) the area percentage in each score class for each theme. Themes 3-5 are represented with binary scores (0 – to exclude, 1 – to keep).*

Figure 13 *(next page) Overview of the five themes and their scoring. Themes 3-5 are shown with a binary score (0 – to exclude, 1 – to keep). Note that the maps are visualised with a continuous colour-scheme (0.1 in each class), same as in* ***Figure 14****.*

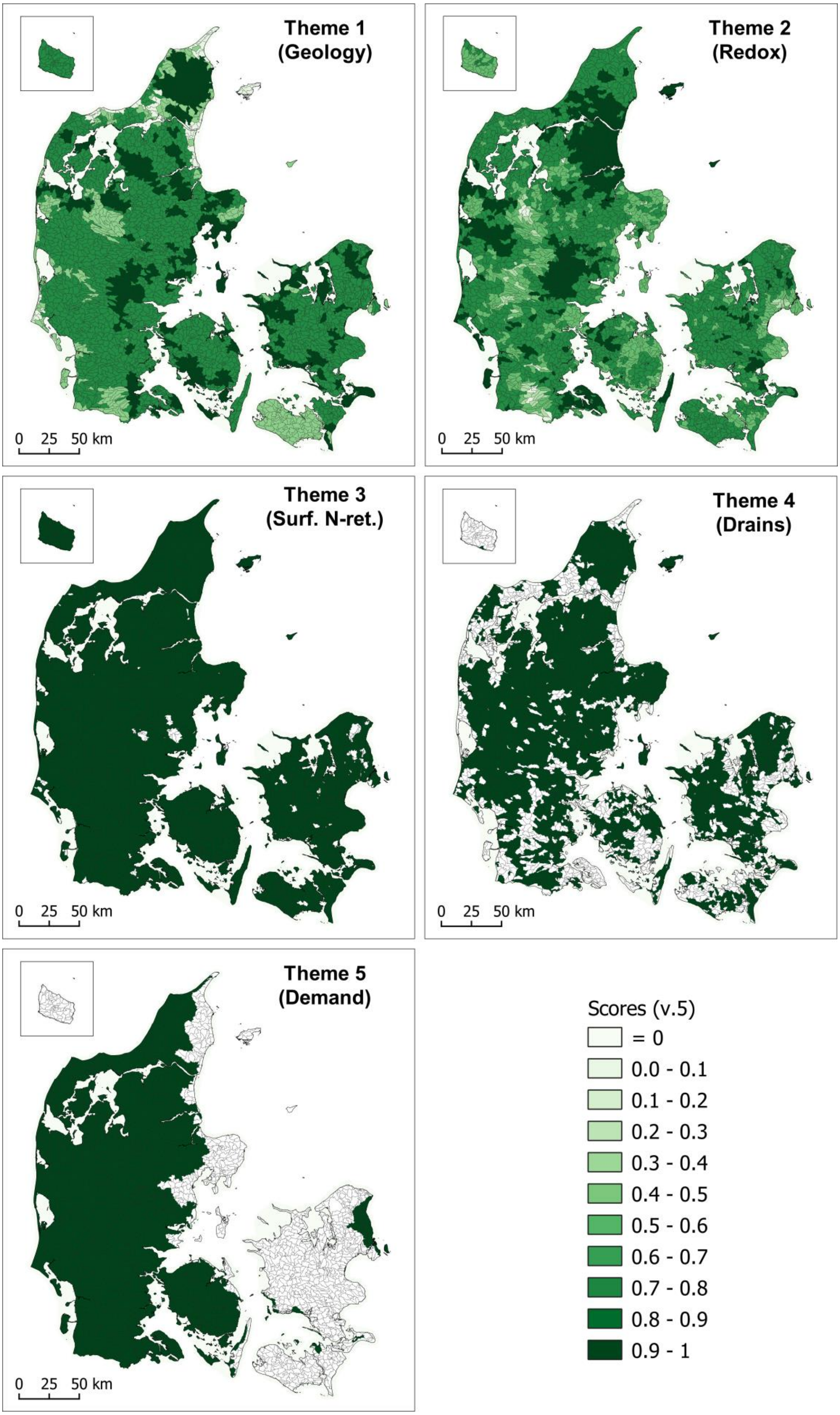
Theme 1
(Geology)
0 25 50 km
Theme 2
(Redox)
0 25 50 km
Theme 3
(Surf. N-ret.)
0 25 50 km
Theme 4
(Drains)
0 25 50 km
Theme 5
(Demand)
0 25 50 km
Scores (v.5)
= 0
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1

Table 2 *ID15 catchments (n) and the corresponding area (ha) for each theme and each score*

Score	Theme 1 (Geology)		Theme 2 (Redox)		Theme 3 (Surf. N-ret.)		Theme 4 (Drains)		Theme 5 (Demand)	
	n	*ha*	*n*	*ha*	*n*	*ha*	*n*	*ha*	*n*	*ha*
0	-	-	-	-	135	66,791	1224	1,315,560	1123	1,291,648
0.2	89	100,853	19	19,473	-	-	-	-	-	-
0.4	-	-	84	89,702	-	-	-	-	-	-
0.5	402	485,444	-	-	-	-	-	-	-	-
0.6	-	-	685	866,995	-	-	-	-	-	-
0.8	2144	2,704,371	1880	2,475,310	-	-	-	-	-	-
1	715	1,015,556	683	854,814	3216	4,239,503	2127	2,990,734	2228	3,014,645
-	1	70	-	-	-	-	-	-	-	-
Total	3351	4,306,294	3351	4,306,294	3351	4,306,294	3351	4,306,294	3351	4,306,294

4.3 The prioritization tool

The maps resulting from the application of the three steps of the MapField prioritization tool are shown in ***Figure 14***, where the final prioritization map is shown at Step 3. **Table 3** shows an overview of the total area for each scoring value at each of the three steps, while **Table 4** shows the ID15 catchments with the highest score (=1) grouped by the VPII coastal catchments.

The ID15 catchments with the highest score of 1 in Step 3 are mainly located in Jutland. This is due to exclusion of many catchments in lowland areas and clayey areas, and because many areas in Zealand and the Eastern part of Jutland are excluded due to no demands for N-reduction in VPII (***Figure 14***).

The 3351 ID15 catchments are prioritized in Step 1 with a final score from 0 to 1 covering the total area of Denmark of 4,306,204 ha.

In Step 1 in the prioritization tool, the highest score of 1 is given to 180 ID15 catchments (=253,230 ha), in Step 2 it is given to 112 ID15 catchments (=182,874 ha), and in the final prioritization map (Step 3) it is given to 94 ID15 catchments (=158,096 ha) (**Table 3**).

In the final prioritization map (Step 3), 51% of the land surface (=2,204,203 ha) with 1947 ID15 catchments is excluded, having the lowest score of 0. One catchment with an area of 70 ha had missing information for Theme 1 (Geology), so no scores have been calculated for it (**Table 3**).

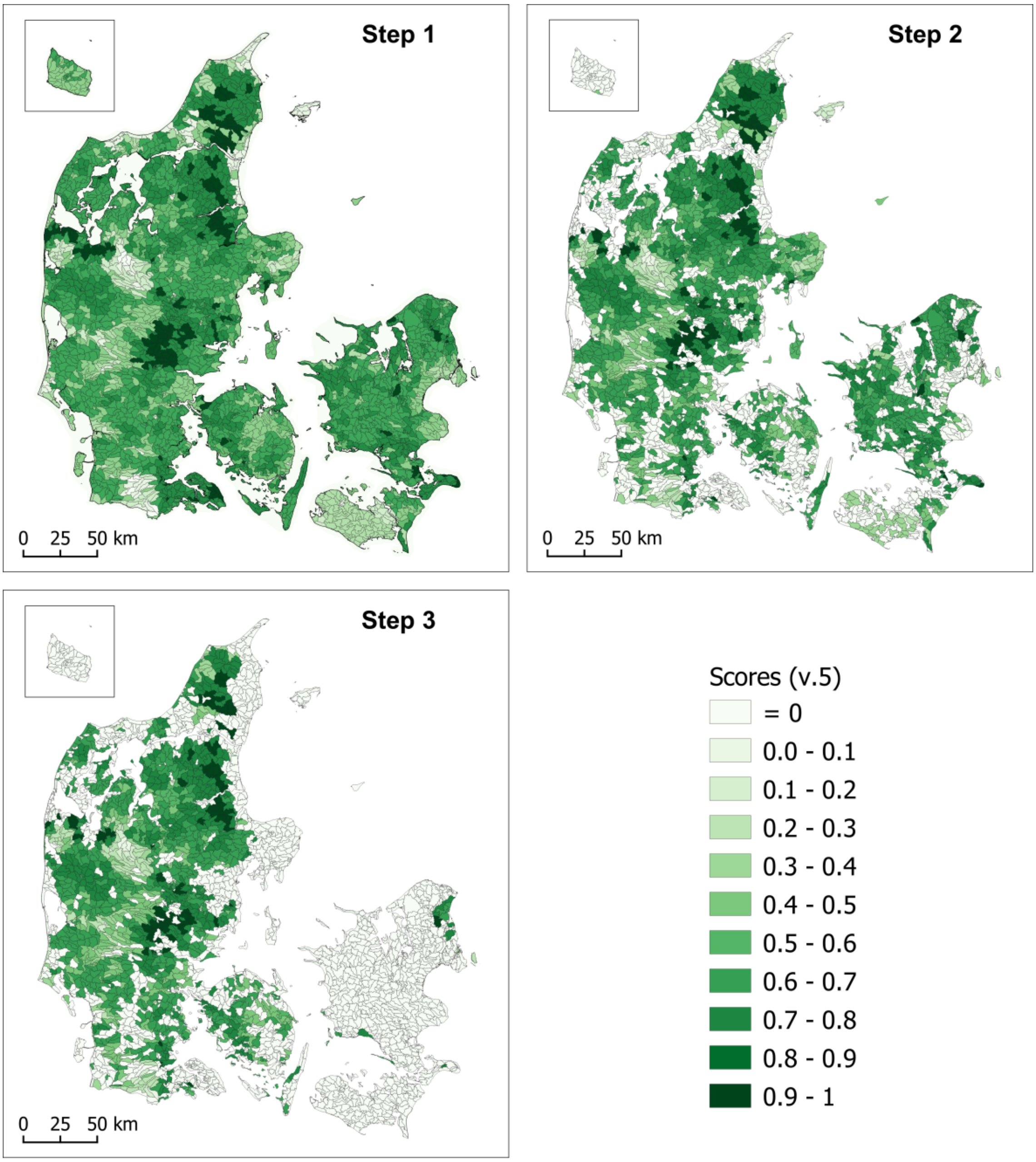

***Figure 14** Applying the 3-step prioritization approach to derive the prioritization map at ID15 catchment level (Step 3). Step 1: Subsurface complexity map (multiplying Themes 1 & 2), Step 2: Surface N-retention and drain maps (excluding catchments due to Themes 3 & 4), Step 3: N-reduction demand (excluding ID15 catchments located in coastal catchments without N-reduction demand). (See also **Table 3**).*

The three coastal catchments with the largest numbers of ID15 catchments with a high prioritization in Step 3 (score=1) are 1) Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak, 2) Randers Fjord – Grund Fjord, Randers Mellerup and ydre, and 3) Ringkøbing Fjord when the postponed N-requirements from VPII are used (**Table 4**).

Table 3 *The ID15 catchments (n) and the corresponding area (ha) at each step of the prioritization tool; the table also shows the percentage calculated based on the number of ID15 catchments and the area in each score.*

Score	Step 1		Step 2		Step 3		Step 1		Step 2		Step 3	
	n	*ha*	*n*	*ha*	*n*	*ha*	*%(n)*	*%(ha)*	*%(n)*	*%(ha)*	*%(n)*	*%(ha)*
0	-	-	1306	1,363,650	1947	2,204,203	-	-	39.0	31.7	58.1	51.2
0.1	11	16,302	6	9,791	5	9,711	0.3	0.4	0.2	0.2	0.1	0.2
0.12	5	2,256	2	1,435	1	275	0.1	0.1	0.1	0.0	0.0	0.0
0.16	52	48,801	14	8,061	14	8,061	1.6	1.1	0.4	0.2	0.4	0.2
0.2	74	92,313	36	44,922	25	29,668	2.2	2.1	1.1	1.0	0.7	0.7
0.3	123	145,996	90	119,689	74	101,492	3.7	3.4	2.7	2.8	2.2	2.4
0.32	43	46,747	26	28,070	17	23,679	1.3	1.1	0.8	0.7	0.5	0.5
0.4	190	224,672	91	111,669	38	45,399	5.7	5.2	2.7	2.6	1.1	1.1
0.48	441	555,377	261	360,272	186	279,365	13.2	12.9	7.8	8.4	5.6	6.5
0.5	50	62,663	17	24,536	12	12,547	1.5	1.5	0.5	0.6	0.4	0.3
0.6	116	163,366	83	122,194	34	53,571	3.5	3.8	2.5	2.8	1.0	1.2
0.64	1239	1,613,122	773	1,130,054	538	815,040	37.0	37.5	23.1	26.2	16.1	18.9
0.8	826	1,081,377	533	799,008	365	565,117	24.6	25.1	15.9	18.6	10.9	13.1
1	**180**	**253,230**	**112**	**182,874**	**94**	**158,096**	**5.4**	**5.9**	**3.3**	**4.2**	**2.8**	**3.7**
-	1	70	1	70	1	70	0.0	0.0	0.0	0.0	0.0	0.0
Total	3351	4,306,294	3351	4,306,294	3,351	4,306,294						

Table 4 *The ID15 catchments with the highest score in the prioritization map at Steps 2 and 3 grouped by coastal catchment (VPII) showing numbers (n) and total area (ha) of the ID15 catchments; the postponed demand from VPII is provided, as well as indications of the theme (T3, T4, T5) that was responsible for exclusion of the catchment(s).*

Coastal catchment	Vandplan II		ID15 excluded at			ID15 with score 1 (n)			ID15 with score 1, area (ha)		
	Demand (tN/y)	Postponed (tN/y)	T3	T4	T5	Step 1 (n)	Step 2 (n)	Step 3 (n)	Step 1 (ha)	Step 2 (ha)	Step 3 (ha)
Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning og Langerak (156)	2122.1	884.3	-	x	-	50	32	32	77,502	56,331	56,331
Randers Fjord - Grund Fjord, Randers Mellerup og ydre (135, 136, 137)	684.3	48.6	x	x	-	23	17	17	34,413	27,710	27,710
Ringkøbing Fjord (132)	1422.2	983.5	-	x	-	14	9	9	27,981	18,382	18,382
Mariager Fjord, indre og ydre (159, 160)	182.4	44.9	-	x	-	7	6	6	12,149	10,892	10,892
Vejle Fjord, indre og ydre (122, 123)	237.2	44.2	-	x	-	7	4	4	7,236	2,009	2,009
Hjarbæk Fjord (158)	823.2	546.1	-	-	-	4	4	4	8,828	8,828	8,828
Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord og Lovns Bredning (157)	681.9	430.4	-	-	-	4	4	4	6,863	6,863	6,863
Horsens Fjord, ydre og indre (127, 128)	347.7	175.1	-	-	-	4	4	4	5,989	5,989	5,989
Åbne vandomr. Gr. I – Skagerak og Vesterhavet (221)	186.3	38.7	-	-	-	3	3	3	7,743	7,743	7,743
Åbne vandomr. Gr. VI – Øresund og Køge Bugt og Østersøen (6, 9)	269.8	239.4	x	x	-	6	2	2	3,581	3,127	3,127
Nissum Fjord, ydre, mellem og Felsted Kog (129, 130,131)	719.5	488.8	-	x	-	3	2	2	6,454	4,550	4,550
Åbne vandomr. Gr. IV – Lillebælt (216, 217, 224)	428.5	140.7	-	x	-	4	1	1	7,023	695	695
Odense Fjord, ydre og Seden Strand (92, 93)	549.3	203.5	-	x	-	2	1	1	403	52	52
Åbenrå Fjord (102)	62.5	38.5	-	x	-	2	1	1	1,009	451	451
Åbne vandomr. Gr. I – Skagerak og Vesterhavet (133)	4.8	0.3	-	x	-	2	1	1	1,959	1,303	1,303
Juvre Dyb, Lister Dyb, Knudedyb og Grådyb (107, 111, 120, 121)	1750.3	1093.6	-	-	-	1	1	1	2,026	2,026	2,026

Coastal catchment	Vandplan II		ID15 excluded at			ID15 with score 1 (n)			ID15 with score 1, area (ha)		
	Demand (tN/y)	Postponed (tN/y)	T3	T4	T5	Step 1 (n)	Step 2 (n)	Step 3 (n)	Step 1 (ha)	Step 2 (ha)	Step 3 (ha)
Nybøl Nor, Flensborg Fjord, indre og ydre (110, 113,114)	72.6	20.4	-	-	-	1	1	1	770	770	770
Norsminde Fjord (146)	70.1	33	-	-	-	1	1	1	374	374	374
Åbne vandomr. Gr. II – Kattegat (154, 222, 225)	-518.7	0	-	-	x	8	8	0	14,966	14,966	-
Åbne vandomr. Gr. VI – Øresund og Køge Bugt og Østersøen (46)	22.4	0	x	x	x	8	2	0	1,545	45	-
Karrebæk Fjord (35)	321.1	0	x	-	x	3	2	0	1,828	517	-
Ebeltoft Vig (141)	-3.6	0	-	x	x	3	1	0	1,979	875	-
Stege Bugt (48)	-4.1	0	-	x	x	3	1	0	3,842	1,251	-
Århus Bugt, Kalø Vig, Begtrup Vig og Knebel Vig (144, 145, 147)	-221.5	0	-	x	x	3	1	0	3,361	1,659	-
Roskilde Fjord, indre (2)	20	0	-	-	x	1	1	0	2,895	2,895	-
Åbne vandomr. Gr. VII – Østersøen (44, 208)	-29.8	0	-	-	x	1	1	0	1,100	1,100	-
Åbne vandomr. Gr. II – Kattegat (200, 205)	-51.8	0	-	-	x	1	1	0	1,471	1,471	-
Als Fjord, Als Sund, Augustenborg Fjord (103, 104, 105)	186.7	100.2	-	x	-	5	0	0	5,059	-	-
Roskilde Fjord, ydre (1)	10.5	0	x	x	x	3	0	0	364	-	-
Helnæs Bugt (87)	61.3	5.6	-	x	-	2	0	0	2,194	-	-
Lister Dyb (111), Vidå-Kruså delen	307.5	177.9	-	x	-	1	0	0	325	-	-
Overall		**5737.7**				**180**	**112**	**94**	**253,230**	**182,874**	**158,096**

5 Demonstration in the case studies

The eight case studies from rOPEN (Javngyde and Sillerup) and MapField (LOOP 2, 3, 4 and 6, and the two demo sites in Salling) are used for demonstrating the performance of the prioritization tool according to the five themes.

Figure 15 shows the ranking of these case studies based on the final prioritization map at Step 3, and the scores for all themes and the three steps for these ID15 catchments are provided in ***Table 5***. The maps of the fraction of N-transport through drains and ditches at the ID15 catchment level is shown in ***Figure 16***. The highest possible score is 1, which shows that the area has a high priority for implementing the N-MAP concept.

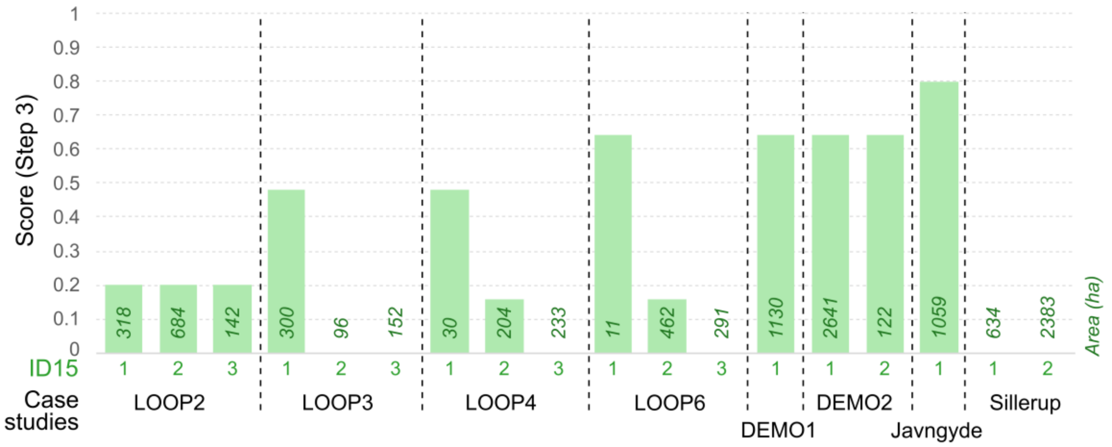

Figure 15 *Ranking of the case studies based on the final prioritization map (Step 3); note that some of the case studies cover multiple ID15 catchments, the specific area is provided as well (numbers within the bars).*

5.1 Javngyde

Javngyde has the highest score of all the eight case studies, with a total score of 0.8. This is due to high scores in all the five themes, as described here:

- The geological complexity is moderate to high (score T1 = 0.8) due to a hilly young glacial landscape. The detailed investigations in rOPEN showed that this is due to glaciotectonics with e.g. thrusted structures (Kim et al., 2019; Sandersen & Kallesøe, 2021).
- The redox complexity is high (score T2 = 1) with a large difference (ca. 23 m) between the first redox interface and the depth to nitrate-containing groundwater. The detailed geochemical investigations in rOPEN support the high redox complexity as both geological window and thrusted redox architectures have been identified; however, the data density is relatively low (Kim et al., 2019; Hansen et al., 2021).
- The surface water N-retention is 78.1% (score T3 = 1), and the N-transport in drains is 78% (score T4 = 1) meaning that they do not exceed the thresholds for exclusion. However, the case study is close to the threshold values as the catchment is placed

in the upper part of the Gudenå catchment with a relatively high fraction of N-transport though drains. See the location in ***Figure 16***.

- The case study has postponed N-reduction requirements in VPII (score T5 = 1).

5.2 Sillerup

Sillerup has the lowest total score of zero in both ID15 catchments in the case study area because of a high degree of N-transport in drains. The following explanations are given to the five themes:

- The geological complexity is moderate to high (score T1 = 0.8) due to a hilly young glacial landscape. The detailed investigations in rOPEN showed that this is due to glaciotectonics with e.g. geological windows (Kim et al., 2019; Sandersen & Kallesøe, 2021).
- The redox complexity is high (score T2 = 1) with a large difference (ca. 22 m) between the first redox interface and the depth to nitrate-containing groundwater in local areas. The detailed geochemical investigations in rOPEN support the high redox complexity as a geological window has been identified, however the data density is relatively low (Kim et al., 2019; Hansen et al., 2021).
- The surface water N-retention is low with 13.9 and 27.7% for the two ID15 catchments within the case study (score T3 = 1) because of the vicinity to the Kattegat sea. The fraction of N-transport in drains is high with ca. 93% (score T4 = 0) due to near-surface clayey conditions. See the location in ***Figure 16***.
- The case study is in a coastal catchment with postponed N-reduction requirements in VPII (score T5 = 1).

5.3 LOOP 2 – Himmerland

LOOP 2, located in Himmerland, has a low total score of 0.2 in all three ID15 catchments in the case study area because of a relatively low redox complexity. The following explanations are given to the five themes:

- The geological complexity is high (score T1 = 1) due to a young glacial landscape near the ice-margins of the last glaciation. The detailed investigations in MapField showed that this is due to glaciotectonics with e.g. geological windows (Kim et al., 2021; Sandersen & Kallesøe, 2021).
- The redox complexity is low (score T2 = 0.2) with a low difference (ca. 1-4 m) between the first redox interface and the depth to nitrate-containing groundwater. The detailed geochemical investigations in MapField reveal the same redox conditions as are included in the national N-model with a hilly landscape and a lowland area, where nitrate-containing water is flowing underneath upper reduced postglacial layers (Kim et al., 2021; Hansen et al., 2021).
- The surface water N-retention is low, varying from ca. 13-30% (score T3 = 1), because of the vicinity to Limfjorden with no major lakes. The fraction of N-transport in drains in this sandy catchment is relatively low as well, at ca. 27-45% (score T4 = 1). See the location in ***Figure 16***.

- The case study is in a coastal catchment with postponed N-reduction requirements in VPII (score T5 = 1).

5.4 LOOP 3 – Ejer Bavnehøj

LOOP 3, located at Ejer Bavnehøj, has the lowest total score of zero in ca. 45% of the area because of the fraction of N-transport in drains in two of the ID15 catchments in the study case. The remaining 55% of the case study has a total score of 0.48 because of medium high score in geological complexity (score T1 0.8) and medium redox complexity (score T2 = 0.6). The following explanations are giving to the five themes:

- The geological complexity is medium high (score T1 = 0.8) due to a hilly young glacial landscape. The detailed investigations in MapField showed that this is due to glaciotectonics with e.g. geological windows (Madsen et al., 2021; Sandersen & Kallesøe, 2021).
- The redox complexity is low to medium (score T2 = 0.2-0.6) with a difference of ca. 4-13 m between the first redox interface and the depth to nitrate-containing groundwater. The detailed geochemical investigations in MapField showed rather simple redox conditions with only complex redox conditions to the west with a geological window redox architecture (Madsen et al., 2021). However, redox complexity is relatively uncertain in the area due to sparse data for the deeper part, probably due to constraints on drilling possibilities for drinking water.
- The surface water N-retention varies from ca. 66-68% (score T3 = 1), and the N-transport in drains is high, 87-100% (score T4 = 1 or 0). See the location in ***Figure 16***.
- The case study is in a coastal catchment with postponed N-reduction requirements in VPII (score T5 = 1).

5.5 LOOP 4 – Lillebæk

LOOP 4, located at Lillebæk on Funen, has total scores ranging from 0-0.48 because of different degrees of drainage and redox complexity. The following explanations are given to the five themes:

- The geological complexity is moderate to high (score T1 = 0.8) due to a hilly young glacial landscape. The detailed investigations in MapField showed that this is due to a glacial moraine landscape in the southeastern part and a dead ice landscape with moraine and kame hills in the western part (Sandersen & Kallesøe, 2021).
- The redox complexity is low to medium (score T2 = 0.2-0.6) with a difference of ca. 4-11 m between the first redox interface and the depth of nitrate-containing groundwater. However, the detailed geological and geochemical investigations in MapField showed a deeper nitrate-containing aquifer and multiple oxic groundwater layers underneath the upper reduced layers indicating complex redox conditions.
- The surface water N-retention is very low, from ca. 1-6% (score T3 = 1). The N-transport in drains and ditches is high and varies from 75-100% (score T4 = 1 or 0). See the location in ***Figure 16***.

- The case study is in a coastal catchment with postponed N-reduction requirements in VPII (score T5 = 1).

5.6 LOOP 6 – Bolbro

LOOP 6, located at Bolbro in Southern Denmark, has total scores ranging from 0-0.64 because of different degrees of geological and redox complexity and drainage in the area. The following explanations are given to the five themes:

- The geological complexity is low to moderate, and moderate to high (score T1 = 0.5 or 0.8) due to the dominating Tinglev outwash plain with low complexity and small parts of the study area located on glacial landscape remnants of pre-Weichselian age (hill islands) with moderate to high complexity. The detailed investigations in MapField confirm these conditions (Sandersen & Kallesøe, 2021).
- The redox complexity is low to high (score T2 = 0.2 or 0.8) with a difference of ca. 1-16 m between the first redox interface and the depth to nitrate-containing groundwater. This is due to simple redox conditions in the outwash plain and more complicated redox conditions in the hill island. The detailed geochemical investigations in MapField confirm these conditions.
- The surface water N-retention is relatively low, from ca. 28-34% (score T3 = 1). The N-transport in ditches in the riparian zone is relatively high and varies from 69-98% (score T4 = 1 or 0). See the location in ***Figure 16***.
- The case study is in a coastal catchment with postponed N-reduction requirements in VPII (score T5 = 1).

5.7 Demo sites – Salling

The two demo sites in Salling have similar scoring with a relatively high total score of 0.64. The following explanations are given to the five themes:

- The geological complexity is moderate to high (score T1 = 0.8) due to a young clay-dominated glacial landscape. The detailed investigations in MapField confirm these conditions with ice-marginal hills and many crossing buried valleys with sandy infill in the subsurface between clayey parts, creating a complex geological setting (Sandersen & Kallesøe, 2021).
- The redox complexity is medium high (score T2 = 0.8) with a difference of ca. 16-18 m between the first redox interface and the depth to nitrate-containing groundwater. This is due to complex conditions in the subsurface with nitrate-containing groundwater in the sandy buried valleys and more reduced conditions in the clayey parts of the catchment. The detailed geochemical investigations in MapField confirm these conditions.
- The surface water N-retention is low from ca. 6-10% (score T3 = 1) due to the direct vicinity to the Limfjord. The fraction of N-transport in drains varies from 52-70% (score T4 = 1). See the location in ***Figure 16***.
- The case study is in a coastal catchment with postponed N-reduction requirements in VPII (score T5 = 1).

Table 5 *Information about the ID15 catchments that cover the case studies including the input data and the scores for each theme, as well as the scoring at the three steps. "Label" is the same as the x-axis labelling for the ID15 catchments in* ***Figure 15****.*

Case Study	**ID15 v.2.2**	**Label**	**Area (ha)**	**Data T1** Geol.	Cover (%)	**Data T2** Med dif. (m)	**Data T3** RedSurf (%)	**Data T4** N-Drain (%)	**Scores** T1	T2	T3	T4	T5	**Step 1**	**Step 2**	**Step 3**
LOOP 2	37430697	1	318	H	41	-4.1	30.3	27.0	1	0.2	1	1	1	0.2	0.2	0.2
	37430695	2	684	H	37	-0.6	18.3	30.0	1	0.2	1	1	1	0.2	0.2	0.2
	37430696	3	142	H	23	-2.3	13.1	45.3	1	0.2	1	1	1	0.2	0.2	0.2
LOOP 3	35321440	1	300	MH	100	-13.1	68.4	87.4	0.8	0.6	1	1	1	0.48	0.48	0.48
	35327841	2	96	MH	100	-10.9	65.9	100.0	0.8	0.6	1	**0**	1	0.48	**0**	**0**
	35321297	3	152	MH	100	-4.4	66.3	100.0	0.8	0.2	1	**0**	1	0.16	**0**	**0**
LOOP 4	66500003	1	30[a]	MH	97	-10.5	6.0	86.6	0.8	0.6	1	1	1	0.48	0.48	0.48
	66500568	2	204	MH	100	-3.8	3.7	74.7	0.8	0.2	1	1	1	0.16	0.16	0.16
	66500569	3	233	MH	100	-4.0	1.3	100.0	0.8	0.2	1	**0**	1	0.16	**0**	**0**
LOOP 6	16510194	1	11[b]	MH	75	-16.0	34.2	81.2	0.8	0.8	1	1	1	0.64	0.64	0.64
	16510195	2	462	MH	32	-2.5	29.7	69.4	0.8	0.2	1	1	1	0.16	0.16	0.16
	16510620	3	291	LM	97	-1.0	27.8	97.9	0.5	0.2	1	**0**	1	0.1	**0**	**0**
DEMO 1	37470553	1	1130	MH	100	-15.5	6.0	51.6	0.8	0.8	1	1	1	0.64	0.64	0.64
DEMO 2	37470002	1	2641	MH	100	-17.6	8.9	69.5	0.8	0.8	1	1	1	0.64	0.64	0.64
	37470001	2	122[c]	MH	97	-18.2	10.1	52.2	0.8	0.8	1	1	1	0.64	0.64	0.64
Javngyde	35321442	1	1059	MH	93	-23.3	78.1	78.0	0.8	1	1	1	1	0.8	0.8	0.8
Sillerup	54600222	1	634	MH	100	-22.7	27.7	93.3	0.8	0.8	1	**0**	1	0.64	**0**	**0**
	54600020	2	2383	MH	100	-21.8	13.9	92.7	0.8	0.8	1	**0**	1	0.64	**0**	**0**

Note: the entire area of the ID15 catchments is [a] 1217.1 ha, [b] 1886.3 ha, [c] 1604.7 ha.

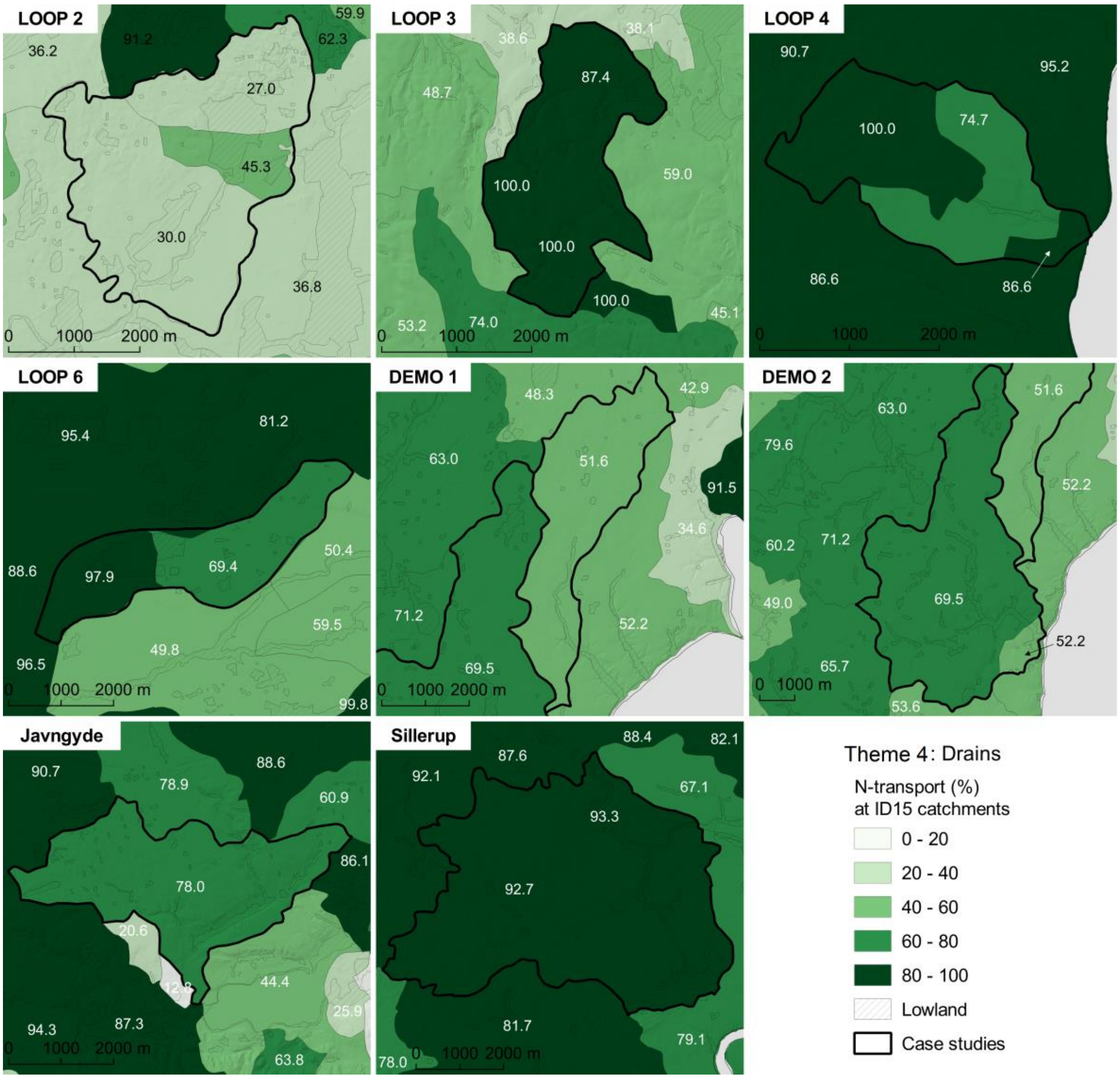

Figure 16 *Maps of the case studies and the fraction of N-transport through drains and ditches at the ID15 catchment level.*

6 Discussion

This chapter discusses the uncertainty and flexibility of the prioritization tool, and how further prioritization can be implemented within the N-MAP concept.

6.1 Prioritization according to groundwater protection

The aim of the prioritization tool is to rank the ID15 catchments and show which of them are most suitable for implementing the N-MAP concept to support cost-efficient targeted N-regulation of agricultural fields for protection of the aquatic environment, the focal point being the coastal aquatic environment.

A prioritization tool that focuses on groundwater protection can be developed based on the similar composite index method of selected themes, however only including the themes appropriate for groundwater protection. In that case, the target units should not be the ID15 catchments but the delineated groundwater bodies or aquifers. Both the geology and redox complexity themes would also be important themes, while the theme for N-reduction requirements should be the one addressing groundwater in the River Basin Management Plan. Another theme could consider the nitrate vulnerability assessments from the national groundwater mapping program.

6.2 Uncertainty and limitations of the themes

The prioritization tool has been developed through many meetings and discussions within the group of contributing authors representing different scientific viepoints, and perspectives from stakeholders, such as farmers and authorities. As previously mentioned, the final prioritization tool is based on the collaboration described above and represents a consensus, or the best compromise, as evaluated by the editors. This section discusses uncertainties related to the five themes of the prioritization tool:

The high-resolution mapping and modelling of the eight case studies in the rOPEN and MapField projects revealed higher subsurface complexity than previously known. Therefore, existing data exhibited limitations on evaluating the local complexity before implementing the N-MAP concept. See Appendix 4 for overview of the current availability of primary data.

Theme 1: Geological complexity. The geological complexity map was developed for this prioritization tool by Sandersen (2021). As written in the report by Sandersen (2021) the map is a basic, low-resolution map, exclusively intended as an input for the MapField prioritization tool, and only for assessments of the expected geological complexity in, and around, selected catchments. The basis for the geological complexity map is the existing map of landscape types from Aarhus University (2005), whereas other types of data and background knowledge have only been used as support in developing the map.

Theme 1 has the following limitations:

- The map illustrates the expected level of geological complexity of the upper ca. 30 meters of the subsurface only.
- The individual landscape types from the Aarhus University (2005) map are delineated based on topographical, geomorphological, geological, and soil maps. The topographical map was in 1:100,000 scale, whereas the other maps were in different scales. This means that there can be inconsistencies between the delineation of the individual landscape types used in the geological complexity map when compared to other maps. This is especially the case for the geomorphological map by Smed (1978) which is in 1:360,000 and not available digitally, and the surface geology map by Jakobsen & Tougaard (2020) available in 1:25,000.
- Sub-categorisation used for the geological units (e.g. for "Young glacial landscape") may be deceptive; even beneath a smooth glacial landscape, intense deformation can be present. This means that the actual geological complexity may be underestimated.

Theme 2: Redox complexity. The redox complexity map was developed based on the machine learning technique Random Forest Regression Kriging used to estimate the national first redox interface (FRI) from Koch et al. (2019) and the depth to nitrate-containing water (AB), and is a further development of the maps in Hansen et al. (2021). It is assumed that the larger the difference between FRI and AB, the higher the redox complexity. Therefore, the difference between the two maps is assumed to be an indication of multiple redox interfaces, hence the redox conditions at that location may be complex.

Theme 2 has the following limitations:

- The two input maps (FRI and AB) are based on different number of observations: 15,601 and 3,167 wells, respectively. Therefore, the data availability for the depth to nitrate-containing groundwater might be a limiting factor.
- The standard deviations are larger for the AB than the FRI, which might be due to deeper levels of the nitrate-containing groundwater (AB) than the first redox interface (FRI) (***Figure 17***). Moreover, the lower number of training data in the AB model may result in elevated uncertainty. Based on the framework presented by Koch et al. (2019), the uncertainty is estimated via a geostatistical residual model. Since the residuals exhibited no spatial correlation, the same variogram model was applied to interpolate the residuals for the entire simulation domain. The variance was subsequently scaled to a local variance, calculated for a 10 km radius in each grid, which explains the circular spatial pattern in ***Figure 17*. ** The circles are less visible for the FRI map, because both the random forest modelling and the residual modelling were done in log space. However, the standard deviation was calculated for the back-transformed maps.
- The same 18 covariates are used to train the two models (Appendix 1, ***Figure 20***). The variables with the largest importance for the FRI map were the wetland classification (34.4%) and the landscape type classification (20.2%). However, these had low importance for the AB map: 0.2% and 9.9%, respectively. The most influential variables for the AB map were the minimum depth of simulated groundwater table (19.3%), the geo-regions classification (35.9%) and the digital elevation model (40.0%), and these had low importance for the FRI map: 9.0%, 5.9%,

and 4.9%, respectively. The rest of the variables had lower relative importance for both maps (0.1% - 7.3%). The selection of variables could to some extend be a limiting factor. It is possible that other or additional variables may need to be considered in future work.

- The nature of the modelled parameters is different. The AB map considers the depth to the top of the deepest screen in each well, where there is nitrate-containing groundwater. This might underestimate the depth of nitrate-containing groundwater and give an unprecise depth determination due to few screens or only one screen with water sampling in each well. On the other hand, the FRI map is based on a change in sediment colors, often from continuous sediment sampling in each well, which also has some degree of uncertainty due to the subjectivity of the determination of the colors.
- Assessing the redox conditions with more certainty requires more detailed investigations.

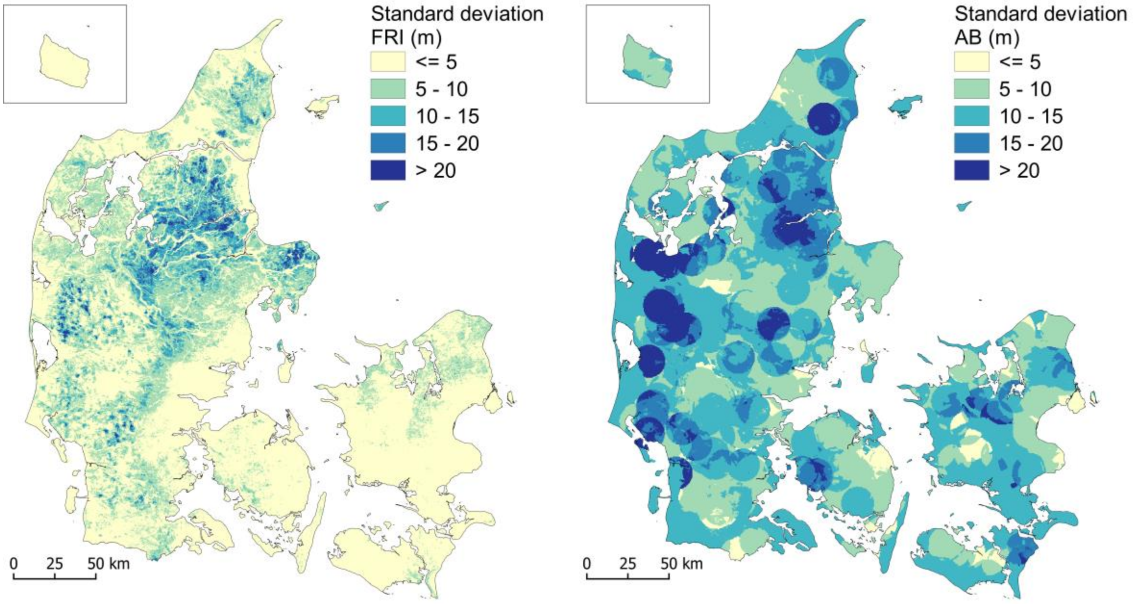

***Figure 17** Standard deviations (SD) for the first redox interface map (FRI, left) and for the depth to nitrate-containing water (AB, right); the SD was calculated based on the maps for +/- 1SD (see Appendix 1, **Figure 21**)*

The performance metrics for both maps (FRI & AB) are shown in **Table 6**. Performance is given based on the coefficient of determination, mean error and root mean squared error from the Random Forest model. The Random Forest model provides an out-of-bag (oob) prediction, which can be interpreted as an independent validation test. The "all" column reflects performance based on the actual model output, i.e. the data were also used for training, which explains the fact that performance is better for "all" than for "oob".

The performance of the FRI model is somewhat poorer than for the AB model. The FRI model is trained against log-transformed values to account for the highly skewed distribution (i.e. skewed towards very shallow redox depths), but performance in the table below is calculated based on back-transformed values.

__Table 6__ Performance metrics for both maps (FRI & AB). "oob" is out-of-bag prediction and can be seen as an independent validation test while "all" reflects the performance based on the actual model output including data for training.

Performance metrics	**FRI**		**AB**	
	oob	all	oob	all
R^2	0.19	0.74	0.37	0.89
Mean Error (m)	1.43	2.29	-0.32	0.12
Root Mean Squared Error (m)	4.46	7.93	14.38	5.92

The experience from MapField shows that redox complexity and architecture are not the only important geochemical parameter for assessing the N-retention in the subsurface. The N-reduction rate is also very important, but this parameter cannot be taken into consideration in the prioritization tool on a national level due to lack of knowledge. However, with time and an increasing number of areas covered by detailed mapping in the coming years, it might be possible to include this parameter as well.

Theme 3: N-retention in surface waters. Estimates for N-retention in surface waters is from the national N-model by Højberg et al. (2021). However, there are no estimates of the uncertainty of N-retention in surface waters. In general, the magnitude of the uncertainty on model results will vary from place to place depending on the actual physical and chemical conditions and the available data (Højberg et al., 2021).

Theme 4: Degree of drainage. Estimates of the fraction of N-transport in drains and ditches also come from the national N-model by Højberg et al. (2021). The drain N-transport is separated from the groundwater N-transport, and water flow in the drains is handled by the groundwater DK-model. However, there are no estimates of the uncertainty of the N-transport in drains.

Theme 5: N-reduction demand. The N-reduction requirements in the coastal catchments according to the implementation of the Water Framework Directive (EC, 2000) in VPII have been assessed based on an extensive data base and the latest scientific knowledge (Miljø- og Fødevareministeriet, 2016). The estimations are well consolidated, when compared to other countries as well, and the uncertainty is estimated to +/- 20% in the individual coastal catchments (Miljø- og Fødevareministeriet, 2016).

6.3 Uncertainty of the prioritization tool

The prioritization tool and the final prioritization map come with an uncertainty that depends on the discussed uncertainty of the individual input data for the themes, their aggregation to the ID15 catchment level and scoring, and the selected method for combining the themes.

It was decided that the resolution of the final prioritization map is the ID15 catchment, not just because this is an actual administration level but also in order not to violate the resolution and data availability of the individual themes.

The multiplication method, and especially the low scores in each of the themes, have a high impact on the final prioritization map. The decision to exclude areas with no requirement for N-reduction, a high fraction of N-transport through drains of > 90%, and a high surface water N-retention of > 80% determines which areas are included in the final prioritization map. On the other hand, the decisions on the scoring of theme 1 (geological complexity) and theme 2 (redox complexity) determine the prioritization of the included ID15 catchments. Therefore, these decisions are crucial for the final prioritization tool and map. As with all other similar methods based on composite indicators, the selection of a scoring system could be criticized for being subjective. The scoring presented here was selected based on expert evaluation of different options.

The prioritization tool presented in this report should be seen as the first version of a prioritization tool, which can be updated and refined when more knowledge and data become available with time and with an increasing number of areas covered with detailed mapping in the coming years.

6.4 Flexibility of the prioritization tool

The construction of the prioritization tool with three steps (***Figure 4***) and with the placement of N-reduction demands in the last theme, number 5, makes it flexible and easy to update, when new N-reduction requirements are agreed on, e.g. for coastal catchments, in VPIII. Then Theme 5 could be updated with the new N-reduction demands for coastal catchments, which should include the annual requirements for targeted N-regulation (6,500 ton N) and the postponed N-reduction (13,100 – 10,800 = 2,300 ton N) as described by The Danish Government (2021).

6.5 Further prioritization in the N-MAP concept

When implementing the N-MAP concept, further prioritization will be done under Step 1 "Reviewing existing knowledge" (see ***Figure 2***) to decide if it is cost-efficient to continue with Steps 2-5.

In Step 1 of the N-MAP concept, the following conditions are considered:

- The farming practices in the catchment area are examined, including evaluation of the agricultural area and the level of N-leaching. The information on percentage of agricultural area within the ID15 catchment could be useful (see Appendix 3).
- The level of requirement for N-reduction is examined in relation to not only the coastal catchment, but also the groundwater and surface waters.
- An overview of existing data availability is established, and the need for new data is considered. The information on primary data availability provided in Appendix 4 could be useful.
- A preliminary overview of the subsurface geology and redox conditions is established to further consider the potential for differentiated N-regulation.

- N-reduction requirements are examined in relation to different parts of the landscape such as lowland areas and the surface water system, and the need for targeted N-regulation and collective N-regulation is considered. Here, information on lowland areas in Appendix 5 is usable.

7 Conclusion

This report presents a prioritization tool including the final prioritization map that was developed through many meetings and discussions within the group of contributing authors, who represent different scientific points of view, as well as perspectives from stakeholders as farmers and authorities. The final prioritization tool is based on the above-described collaboration and represents a consensus, or the best compromise as evaluated by the editors.

The aim of the prioritization tool is to rank and show, which ID15 catchments are most suitable for implementing the N-MAP concept to support cost-efficient targeted N-regulation of agricultural fields for protection of coastal areas. A prioritization tool that focuses on groundwater protection can be further developed based on a similar composite index method of selected themes by only including themes relevant for groundwater protection.

The high-resolution mapping and modelling of the eight case studies in the rOPEN and MapField projects revealed higher subsurface complexity than previously known. Therefore, existing data exhibited limitations on evaluating the local complexity before implementing the N-MAP concept.

Implementation of the N-MAP concept requires further prioritization from a cost-efficient point of view when evaluating the first step of the N-MAP concept.

This analysis should be regarded as the first version of a prioritization tool, which can be updated and refined when more knowledge and data become available when an increasing number of areas are covered by detailed mapping in the coming years.

8 Acknowledgements

This research was supported by the Innovation Fund Denmark project: MapField – Field scale mapping for targeted N-regulation and management (8850-00025B).

Thanks to Hyojin Kim, GEUS, for providing knowledge about the redox conditions at the case study sites and for creating the conceptual figure for N-retention (***Figure 1***), and Lars Troldborg, GEUS, for critical comments.

We also thank MST for participating at the workshops and providing valuable comments on the draft of this report.

9 References

Aarhus University, 2005. Landskabselementer (Landscape elements). DCA - Nationalt Center for Fødevarer og Jordbrug. https://dca.au.dk/forskning/den-danske-jordklassificering (accessed 10 Nov 2021)

The Danish Government, 2019. Retfærdig retning for Danmark. Politisk forståelse mellem Socialdemokratiet, Radikale Venstre, SF og Enhedslisten. https://ufm.dk/ministeriet/regeringsgrundlag-vision-og-strategier/regeringen-mette-rasmussens-forstaelsespapir/retfaerdig-retning-for-danmark_2019-06-25_endelig.pdf (accessed 22 June 2021)

The Danish Government, 2021. Aftale om grøn omstilling af dansk landbrug. https://fm.dk/media/25215/aftale-om-groen-omstilling-af-dansk-landbrug.pdf (accessed 10 Nov 2021)

European Commission (EC), 2000. Directive 2000/60/EC of the European Parliament and of the Council, of 23 October 2000, establishing a framework for community action in the field of water policy. *Off. J. Eur. Communities* 2000, 327, 1–73. http://data.europa.eu/eli/dir/2000/60/oj (accessed 22 June 2021)

Greco, S., Ishizaka, I., Tasiou, M. & Torrisi, G., 2019. On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness. *Soc. Indic. Res.* 141, 61–94. https://doi.org/10.1007/s11205-017-1832-9 (accessed 22 June 2021)

Hansen, B., Voutchkova, D.D., Sandersen, P.B.E., Kallesøe, A., Thorling, L., Møller, I., Madsen, R.B., Jakobsen, R., Aamand, J., Maurya, P. & Kim, H., 2021**.** Assessment of complex subsurface redox structures for sustainable development of agriculture and the environment. *Environ. Res. Lett.* 16. https://doi.org/10.1088/1748-9326/abda6d

Højberg, A.L., Thodsen, H., Børgesen, C.D., Tornbjerg, H., Nordstrøm, B.O., Troldborg, L., Hoffmann, C.C., Kjeldgaard, A., Holm, H., Audet, J., Ellermann, T., Christensen, J.H., Bach, E.O. & Pedersen, B.F., 2021. National kvælstofmodel – version 2020, Metode rapport. De Nationale Geologiske Undersøgelser for Danmark og Grønland. GEUS Specialrapport, pp 104. https://www.geus.dk/Media/637576521860083405/NKM2020_Rapport_18maj2021_web.pdf (accessed 5 Oct 2021)

Jakobsen, P.R. & Tougaard, L., 2020. Danmarks digitale jordartskort 1:25000. Version 5.0. GEUS Report 2020/18, pp 29. https://www.frisbee.geus.dk/geuswebshop/index.xhtml (accessed 10 Nov 2021)

Kim, H., Høyer, A.-S. S., Jakobsen, R., Thorling, L., Aamand, J., Maurya, P.K., Christiansen, A.V. & Hansen, B., 2019. 3D Characterization of the Subsurface Redox Architecture in Complex Geological Settings. Sci. Total Environ. 693, 133583.

https://doi.org/10.1016/j.scitotenv.2019.133583

Kim, H., Sandersen, P.B.E., Jakobsen, R., Kallesøe, A. J., Claes, N., Blicher-Mathiesen, G., Foged, N., Aamand, J. & Hansen, B., 2021. A 3D Hydrogeochemistry Model of Nitrate Transport and Fate in a Glacial Sediment Catchment: A First Step toward a Numerical Model. *Sci. Total Environ. 776*, 146041. https://doi.org/10.1016/j.scitotenv.2021.146041

Kjærgaard, C., Bach, E.O., Greve, M.H., Iversen, B.V. & Børgesen, C.D., 2017. Kortlægning af potentielle områder til etablering af konstruerede minivådområder. DCA-notat fra 19. maj 2017, pp 15.

Koch, J., Stisen. S., Refsgaard, J.C., Ernstsen, V., Jakobsen, P.R. & Højberg, A.L., 2019. Modeling Depth of the Redox Interface at High Resolution at National Scale Using Random Forest and Residual Gaussian Simulation. *Water Resources Research* 55, 2, 1451-1469. https://doi.org/10.1029/2018WR023939 (accessed 22 June 2021)

Madsen, R.B., Kim, H., Kallesøe, A.J., Sandersen, P.B.E., Vilhelmsen, T.N., Hansen, T.M., Christiansen, A.V., Møller, I. & Hansen, B., 2021. 3D Multiple-Point Geostatistical Simulation of Joint Subsurface Redox and Geological Architectures. *Hydrology and Earth System Sciences* 25 (5), 2759–2787. https://doi.org/10.5194/hess-25-2759-2021

Miljø- og Fødevareministeriet, 2016. Vandområdeplan 2015-2021 for Vandområdedistrikt Jylland og Fyn, pp 144. https://mst.dk/media/122170/revideret-jylland-fyn-d-28062016.pdf (accessed 22 June 2021)

Miljø- og Fødevareministeriet, 2018. Aftale om målrettet regulering – Et nyt paradigme for miljøreguleringen af dansk landbrug. https://mfvm.dk/fileadmin/user_upload/MFVM/Aftaletekst_om_maalrettet_regulering.docx.pdf (accessed 22 June 2021)

Møller, A.B., Børgesen, C.D., Bach, E.O., Iversen, B.V. & Moeslund, B., 2018. Kortlægning af drænede arealer i Danmark. DCA Rapport Nr 135, pp 131. https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport135.pdf (accessed 22 June 2021)

rOPEN & MapField, 2021. New concept for field-scale mapping for targeted regulation of N in agriculture. rOPEN, MapField and Innovation Fund Denmark. https://eng.mapfield.dk/Media/637613270542495807/New%20concept%20for%20field-scale%20mapping%20for%20targeted%20regulation%20of%20nitrogen%20in%20agriculture.pdf

Sandersen, P.B.E., 2021**.** A basic geological complexity map for use in the implementation of the MapField concept. GEUS Rapport 2021/37, pp 25. https://eng.mapfield.dk/Media/637602161172274893/GEUS_report_2021_37_A%20basic%20geological%20complexity%20map_MapField.pdf (accessed 10 Nov 2021)

Sandersen, P.B.E. & Kallesøe, A.J., 2021**.** Geological mapping in MapField LOOP-areas and demo sites. GEUS Rapport 2021/36, pp 77.

http://mapfield.dk/Media/637602161326369650/GEUS_report_2021_36_Geological%20mapping%20in%20MapField%20LOOP-areas%20and%20demo%20sites.pdf (accessed 10 Nov 2021)

Sandersen, P.B.E., Kallesøe, A.J., Møller, I., Høyer, A.S., Jørgensen, F., Pedersen, J.B. & Christiansen, A.V., 2021. Utilizing the towed Transient ElectroMagnetic method (tTEM) for achieving unprecedented near-surface detail in geological mapping. Engineering Geology 288, 106125. https://doi.org/10.1016/j.enggeo.2021.106125

Smed. P., 1978. Landskabskort over Danmark (Four sheets). Geografforlaget 1987.

United States Agency International Development (USAID), 2014. Design and Use of Composite Indices in Assessments of Climate Change Vulnerability and Resilience, pp 50. http://www.ciesin.org/documents/Design_Use_of_Composite_Indices.pdf (accessed 22 June 2021)

Appendix 1: Supplementary information for Theme 2 (Redox)

Dataset preparation: depth to NO_3-containing groundwater

The Jupiter data download (28 Jan 2021) contains a computed redox class based on the algorithm from Geovejledning 6 (Hansen and Thorling, 2018) (***Figure 18***) for each sampling point (well-screen) in Denmark, based on the latest sample that had NO_3, Fe, SO_4, and O_2 analyses. The SQL code used for this Jupiter data download is provided in the raw data (*redox_udtraek28012021.xlsx*).

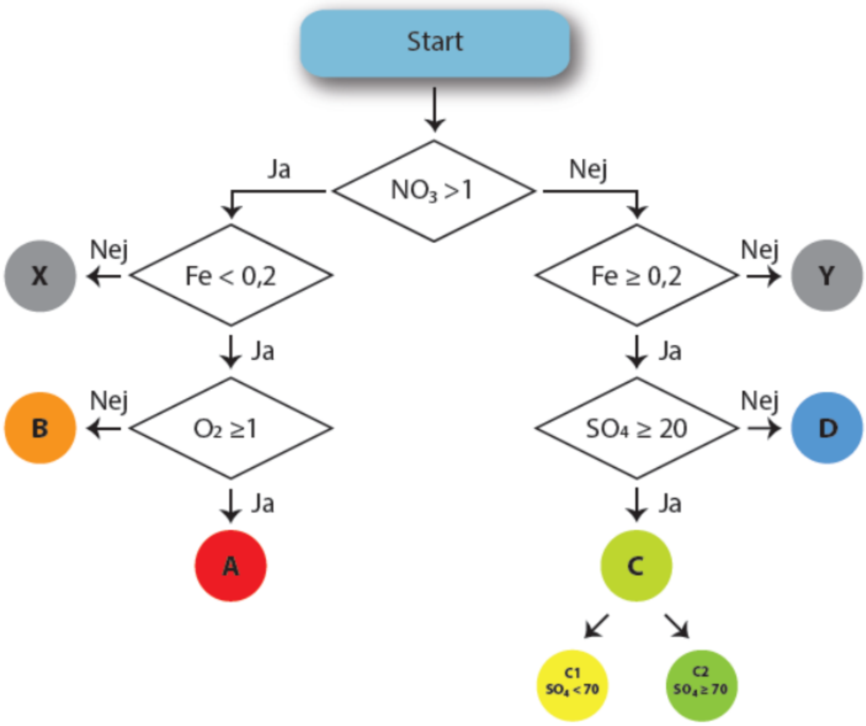

Figure 18 *Algorithm for estimating the redox type in groundwater (Hansen and Thorling, 2018); the concentrations are in mg/l; the redox types are given with capital letters*

The raw dataset contained the following information: GVFOREKOM, BORID, DGUNR, XUTM32EUREF89, YUTM32EUREF89, TERRAENKOTE, INDTAGSNR, INDTAGSID, INDTAG_TOP, INDTAG_BUND, PROEVEID, PROEVEDATO, PROJEKT, DATAEJER, BORANVENDELSE, BORFORMAAL, GRUMO_NR, ATTRIBUT_NITRAT, MAENGDE_NITRAT, ENHED_NITRAT, ATTRIBUT_JERN, MAENGDE_JERN, ENHED_JERN, ATTRIBUT_SULFAT, MAENGDE_SULFAT, ENHED_SULFAT, ATTRIBUT_ILT, MAENGDE_ILT, ENHED_ILT, REDOXVANDTYPE, DATATYPE

To quality assure the redox classification (and NO_3 concentrations) for further use, the following processing was done:

1. Keep only PROJECT codes BK, GRUMO, GRUUDE, LOOP, LOOPUD, GEBKOR
2. Keep only sampling years after 1900 (period 1954-2021)
3. Remove sampling points with missing INDTAG_TOP and INDTAG_BUND
4. Remove sampling points with missing XUTM32EUREF89, YUTM32EUREF89

5. Remove sampling points with NO_3 below detection limit (< DL), where the DL > 1 mg/l (if the detection limit was higher, the redox classification would be wrong)
6. Remove sampling points with NO_3 equal to 0 mg/l (0 mg/l is wrongly recorded)
7. Remove sampling points with negative and zero Fe concentrations (wrongly recorded)
8. Remove sampling points with O_2 concentrations ≥ 15 mg/l; due to either sampling problem or the recording to Jupiter was in % instead of mg/l (wrongly reported unit)
9. Keep only BORANVENDELSE codes: VD, RE, VR, VH, O, PA, N, VP, P, VM, V, M, S, VV, " " (NA allowed)

	BORANVENDELSE (well use)	*Intakes (n)*	*Incl./Excl.*
B	Brunkulsboring	1	X
D	Dybdeboring/dybhulsproduktion	1	X
LO	Oprensning	1	X
KO	Kompensationsboring	2	X
G	Geoteknisk boring/midlertidig grundvandssænkning	3	X
VD	Dambrug	3	√
VS	Permanent grundvandssænkning	5	X
I	Vandinjektion/nedpumpningsboring	7	X
J	Jordvarme op/ned	11	X
RE	Vandindvindingsboring, reserve	18	√
K	Ikke oplyst	22	X
VR	Reserve/Nødvands boring	34	√
VH	Havevanding	45	√
O	Overboret/uddybet og derfor erstattet af nyt DGU nr.	60	√
A	Andet	82	X
VA	Afværgeboring	82	X
PA	Passiv - taget ud af drift midlertidigt	96	√
L	Forureningsbor./miljøundersøg./lossepl./affaldsdep./lov 214	125	X
N	Ingen anvendelse	146	√
VI	Industri/procesvand/kølevand/skylning/grusvaskning	149	X
VP	Privat husholdning/drikkevand udenfor vandværk	568	√
P	Pejleboring	703	√
VM	Markvanding/gartneri	967	√
-		972	√
V	Vandforsyningsboring/nødvandsforsyningsboring/sænkning	1120	√
M	Moniteringsboring/overvågning/kontrol/GRUMO	2725	√
S	Sløjfet/opgivet/opfyldt boring	5328	√
VV	Vandværksboring	5665	√

Boringsanvendelse (well use): Fortæller, hvad boringen bliver anvendt til. Dette kan først konstateres, når boringen er taget i brug, og oplyses derfor oftest via lokaliseringsskema (CodeType = 855).

10. Keep only BORFORMAAL codes: VR, C, VD, S, VH, P, VP, VM, U, M, VV, V, " " (NA allowed)

	BORFORMAAL (well purpose)	*Intakes (n)*	*Incl./Excl.*
B	Brunkulsboring	1	X
VR	Reserve/Nødvands boring	1	√
J	Jordvarme op/ned	2	X
R	Råstofboring f.eks. efter ler/sand/bentonit	2	X
C	Brønd	3	√
LO	Oprensning	3	X
VD	Dambrug	4	√
S	Sløjfet/opgivet/opfyldt boring	5	√
VH	Havevanding	10	√

	BORFORMAAL (well purpose)	*Intakes (n)*	*Incl./Excl.*
VA	Afværgeboring	24	X
I	Vandinjektion/nedpumpningsboring	25	X
G	Geoteknisk boring/midlertidig grundvandssænkning	30	X
VI	Industri/procesvand/kølevand/skylning/grusvaskning	82	X
A	Andet	83	X
P	Pejleboring	96	√
VP	Privat husholdning/drikkevand udenfor vandværk	1193	√
VM	Markvanding/gartneri	282	√
L	Forureningsbor./miljøundersøg./lossepl./affaldsdep./lov 214	481	X
U	Undersøgelsesboring/videnskabelig boring/prøveboring	1605	√
-	No code used	1808	√
M	Moniteringsboring/overvågning/kontrol/GRUMO	2889	√
VV	Vandværksboring	4441	√
V	Vandforsyningsboring/sænkning	6871	√

Boringsformål (purpose): Formålet med boringen (hvad er det planlagt, at boringen skal bruges til), formålet kan bl.a. være Moniteringsboring, Råstofboring, Vandværksboring etc. Boringsformål (CodeType = 17); BOREHOLE table from https://data.geus.dk/tabellerkoder/index.html#myModal

11. Add variable “redox_simple”, combining the REDOXVANDTYPE classes in 3 classes: “A + B”, “C + D”, “X + Y”

12. Add variable “NO3containing”, where if the MAENGDE_NITRAT > 3 (NO_3 > 3 mg/l), the code “yes” is used, otherwise it is “no”

13. Keep only the variables: GVFOREKOM, BORID, DGUNR, XUTM32EUREF89, YUTM32EUREF89, TERRAENKOTE, INDTAGSNR, INDTAGSID, INDTAG_TOP, INDTAG_BUND, "REDOXVANDTYPE", "Year", "redox_simple", "NO3containing"

Overview of the clean dataset (step 13) – note that only a subset of it was used for the machine learning. The clean dataset contains **17,878** sampling points, classified in the following redox types:

REDOX WATER TYPE	*Intakes (n)*	*redox_simple*	*Intakes (n)*
A	2,768	**A + B**	3,547
B	779		
C	7,830	**C + D**	11,594
D	3,764		
X	1,509	**X + Y**	2,737
Y	1,228		

Depth statistics of the entire dataset:

	Depth, meters below terrain						
	min.	Q25	median	Q75	max.	mean	SD
INDTAG_TOP	1	13	21.5	34	137	25.6	18.1
INDTAG_BUND	1.3	17.5	29	45	159.4	34.1	22.9

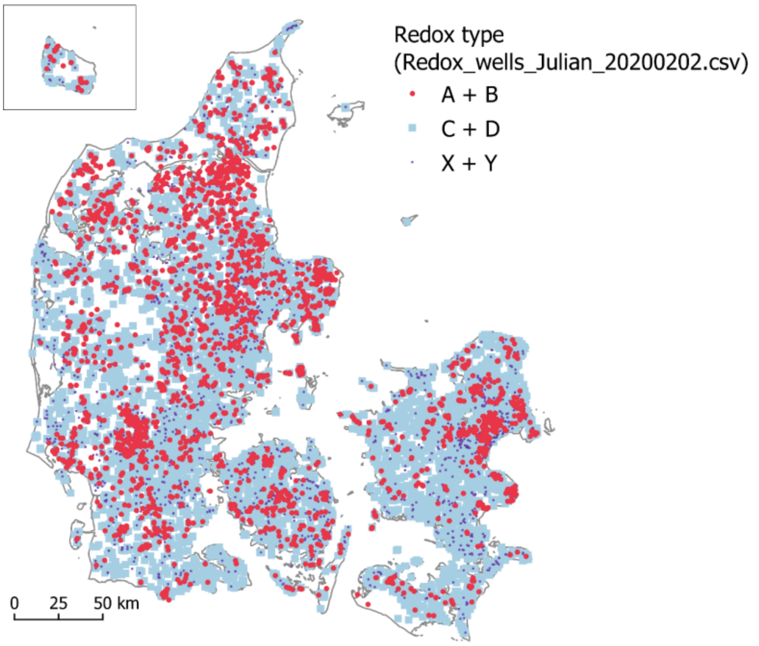

Figure 19 *Wells with determined redox type.*

14. The final dataset used for the machine learning was a subset of the clean dataset, including:

a. Only intakes classified as "A + B" redox type ("redox_simple")
b. For each well only the deepest intake (from a.) was kept

The dataset used further in the machine learning contains the deepest intake with "A + B" redox water type (oxic/anoxic) for 3167 wells and the following variables:

Column name	*Data type*	*Explanation*
BORID	int	well ID, use as key together with INDTAGSNR
DGUNR	chr	well ID, useful for online searches and labeling
XUTM32EUREF89	num	projected X coordinate UTM 32, EUREF 89
YUTM32EUREF89	num	projected Y coordinate UTM 32, EUREF 89
TERRAENKOTE	num	terrain elevation in meters above sea level
INDTAGSNR	int	intake ID (well screen/filter ID), use as key together with BORID
INDTAGSID	int	intake ID, sometimes differs from INDTAGSID
INDTAG_TOP	num	intake top, depth in meters below terrain
INDTAG_BUND	num	intake bottom, depth in meters below terrain
Year	int	sampling year (the redox classification is based on the latest sample with NO_3, Fe, SO_4, O_2)

Machine learning

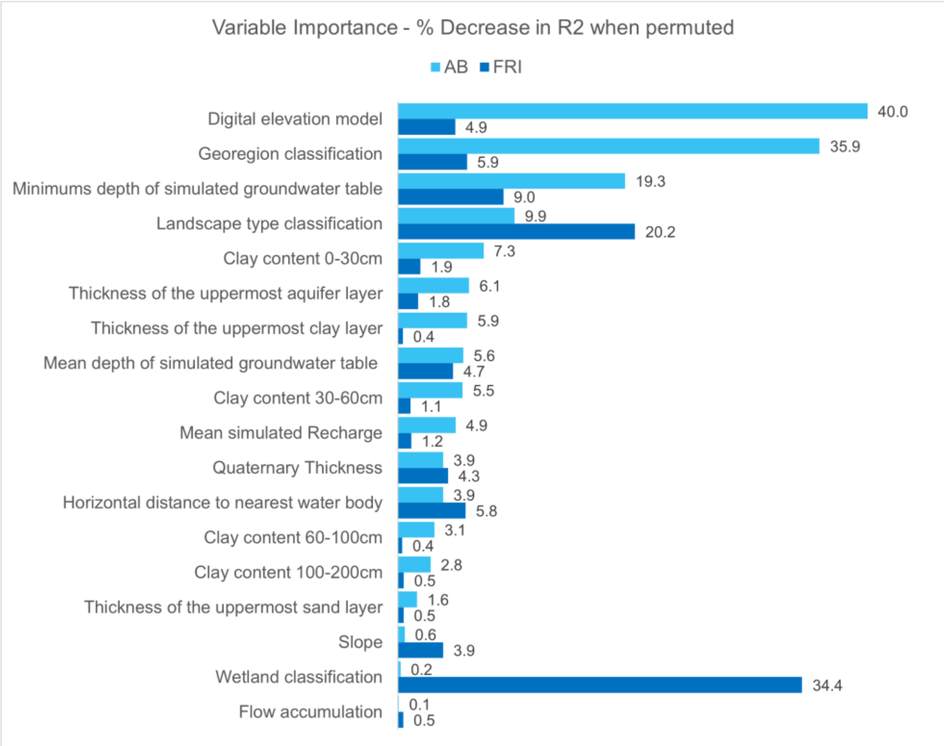

Figure 20 *Importance of the 18 covariates for the two models: (1) depth of nitrate-containing groundwater (AB), and (2) the national first redox interface (FRI)*

Table 7 *Covariates included in the two machine learning models (AB and FRI)*

Name	Description	Source
clay_a	Clay content 0-30cm	Adhikari et al. (2013)
clay_b	Clay content 30-60cm	
clay_c	Clay content 60-100cm	
clay_d	Clay content 100-200cm	
dem	Digital elevation model	Danish Agency for Data Supply and Efficiency (SDFE)
facc	Flow accumulation	
slope	Slope	
hdtochn	Horizontal distance to nearest water body	
quathick	Quaternary thickness	Binzer & Stockmarr (1994)
claydepth	Thickness of the uppermost clay layer	DK-model 2020
sanddepth	Thickness of the uppermost sand layer	
aquiferdepth	Thickness of the uppermost aquifer layer	
HM_phreatic_mean	Mean depth of simulated groundwater table	
HM_phreatic_min	Minimum depth of simulated groundwater table	
HM_recharge	Mean simulated recharge	
georegion	Geo-region classification	Adhikari et al. (2013)
landscape	Landscape type classification	Aarhus University, Danish Centre for Food and Agriculture (DCA) [1]
wetland	Wetland classification	Aarhus University, DCA [2]

[1] The Danish Soil Classification

[2] The Danish SINKs project

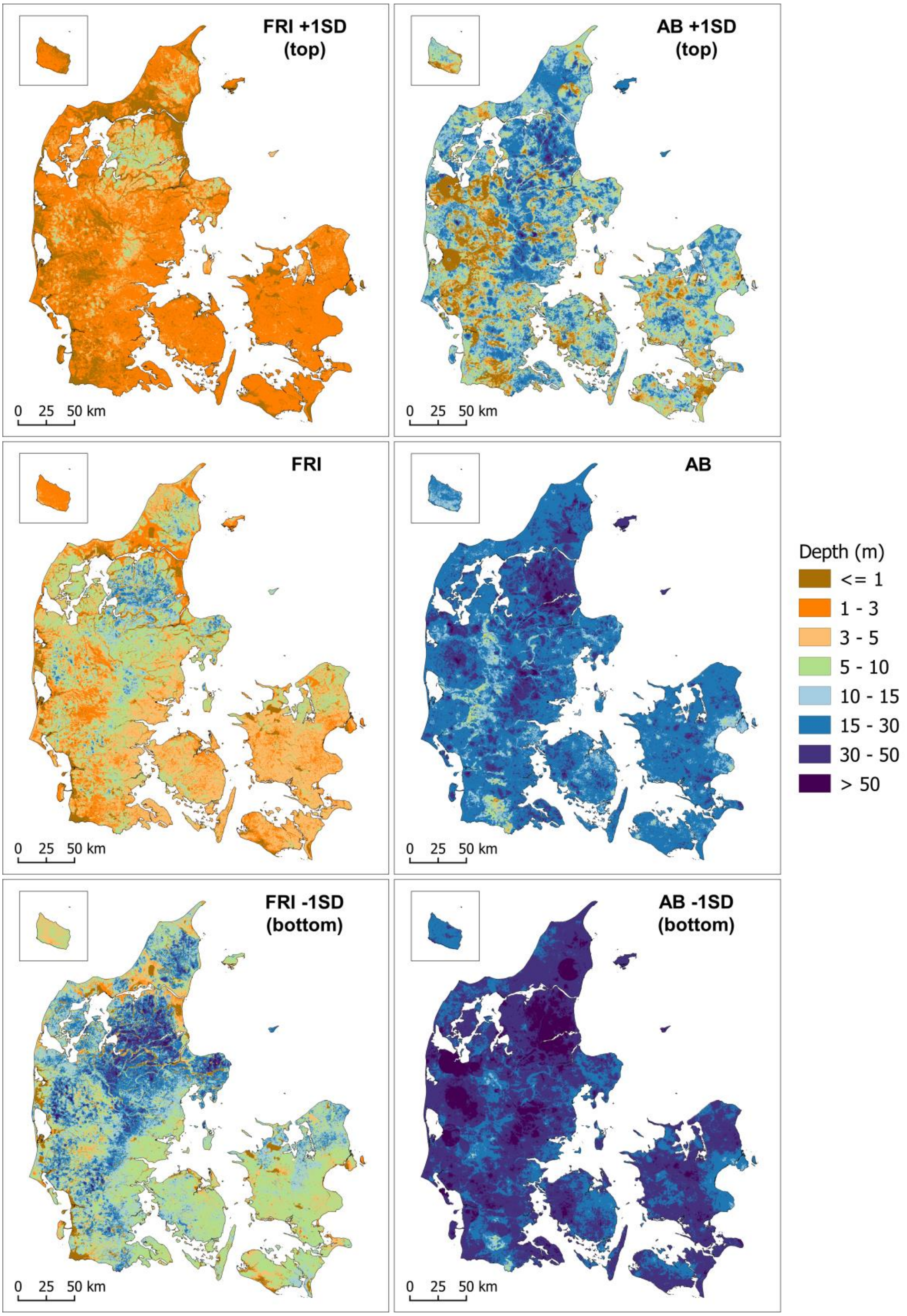

Figure 21 The uppermost redox interface (FRI) with +/-1SD (Koch et al., 2019) and the modelled depth of nitrate-containing groundwater (AB) with +/-1SD, where SD is the standard deviation

Additional references for Appendix 1

Adhikari, K., Kheir, R.B., Greve, M.B., Bøcher, P.K., Malone, B.P., Minasny, B., McBratney, A.B. & Greve, M.H., 2013. High-Resolution 3-D Mapping of Soil Texture in Denmark. Soil Science Society of America Journal, 77: 860-876. https://doi.org/10.2136/sssaj2012.0275

Adhikari K., Hartemink A.E., Minasny B., Bou Kheir R., Greve M.B. & Greve M.H., 2014. Digital Mapping of Soil Organic Carbon Contents and Stocks in Denmark. PLoS ONE 9(8): e105519. https://doi.org/10.1371/journal.pone.0105519

Binzer, K. & Stockmarr, J., 1994. Geological map of Denmark 1: 500 000 (pre-quaternary surface topography of Denmark). Kortserie, DGU, Danmarks Geologiske Undersøgelse.

Hansen B. & Thorling L., 2018. Kemisk grundvandskortlægning, GEO-Vejledning 2018/2, De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS), Copenhagen (Denmark). https://www.geovejledning.dk/2018_2/

Appendix 2: Supplementary material for Theme 4 (Degree of drainage)

Two other options were considered for the Theme 4 on degree of drainage.

1. A map of the drained field areas developed with machine learning approach by DCA (AU) for NaturErhvervstyrelsen (Møller et al., 2018) – a raster with 30.4 m resolution
2. A map showing the simulated flow fraction in drains and ditches based on the DK-model 2020 (Højberg et al., 2021) – a raster with 500 m resolution

Option 1 – the nationwide map of drained field areas (Møller et al., 2018) – gives the probability of agricultural areas to be drained, where each pixel is assigned a probability in the range 13.2% to 87.6%. Møller et al. (2018) present the map in two different ways. The first one shows a binary classification, where each pixel is either drained (> 50% probability) or not drained (≤ 50% probability). The second way shows the estimated probability, classifying each pixel in three classes: low probability of drainage (0-40%), uncertain prediction of drains (40-60%), high probability of drains (60-100%). For the purposes of this analysis, the continuous probability data were used, and based on them, we calculated a median probability for each ID15 catchment (***Figure 22***).

The major point of discussion with respect to *Option 1* was how well it represents the actual systematically drained areas and the flow of water in the drains in Denmark.

Option 2 – the simulated flow fraction in drains and ditches (Højberg et al., 2021) – represents the proportion of infiltration (simulated with the DK-model) that is led directly through the drain system to the surface water bodies for the winter period (Nov-March), ***Figure 23***. The drain transport happens (is activated) when the water level is higher than the drain elevation. The map shows the mean of the monthly means for the winter months in the period 1990-2018 [(Højberg et al., 2021), p. 35]. The small streams ("interne vandløb") incl. small watercourses, ditches, and open drains are represented via the DK-model's drain system. The conceptualizing of the drain system in the DK-model is done by *"regionalization of land-use and topographic variability"* [(Højberg et al., 2021), p. 51].

The major point of discussion with respect to *Option 2* was that it only shows the water flow, not the flow of N.

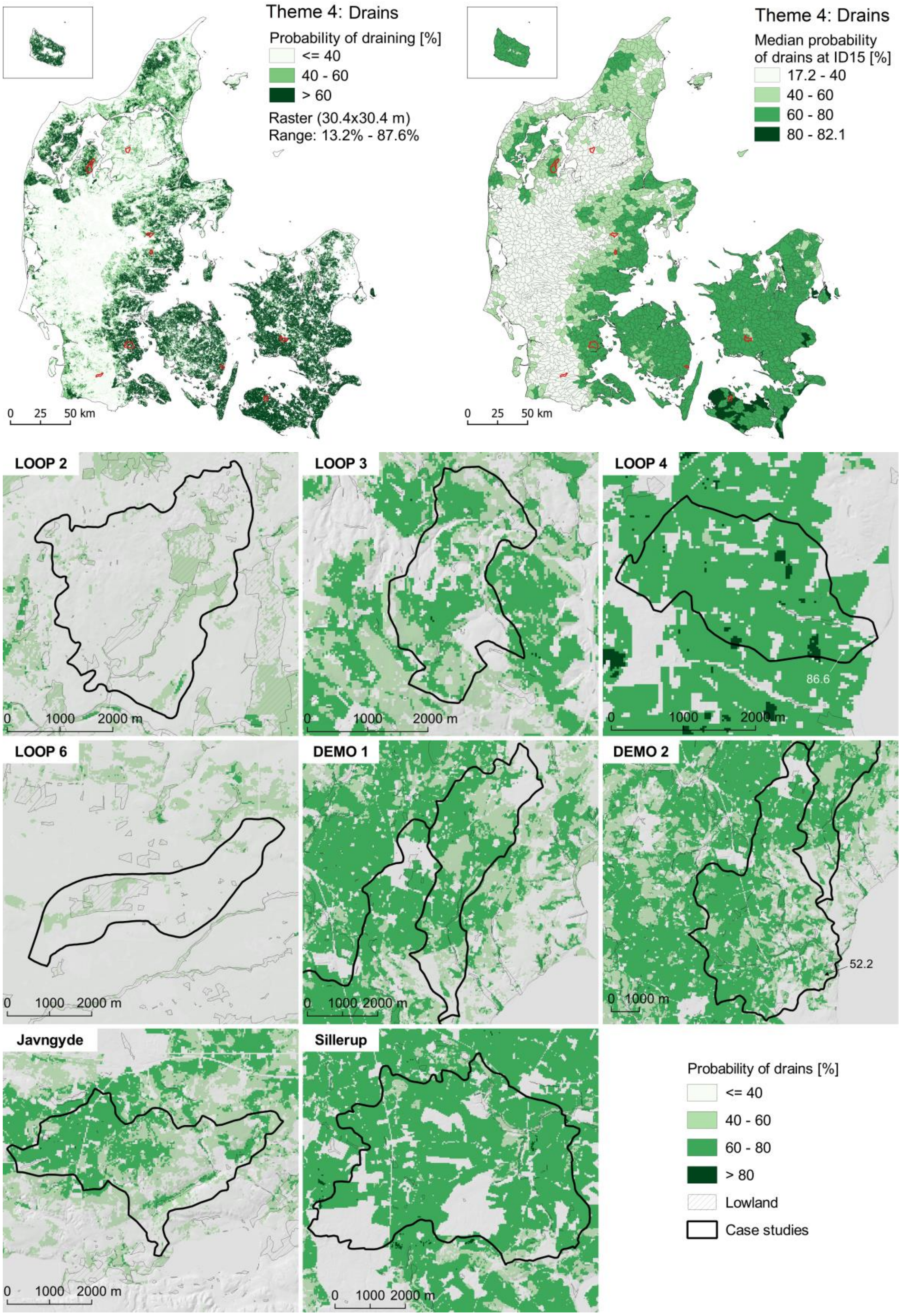

Figure 22 *Estimated probability of draining (Møller et al., 2018) (left) and median probability of drains within ID15 catchment (right). On the case studies maps, the transparent terrain shadow (DHM, Kortforsyningen) gives a greyish tint to the lightest categories.*

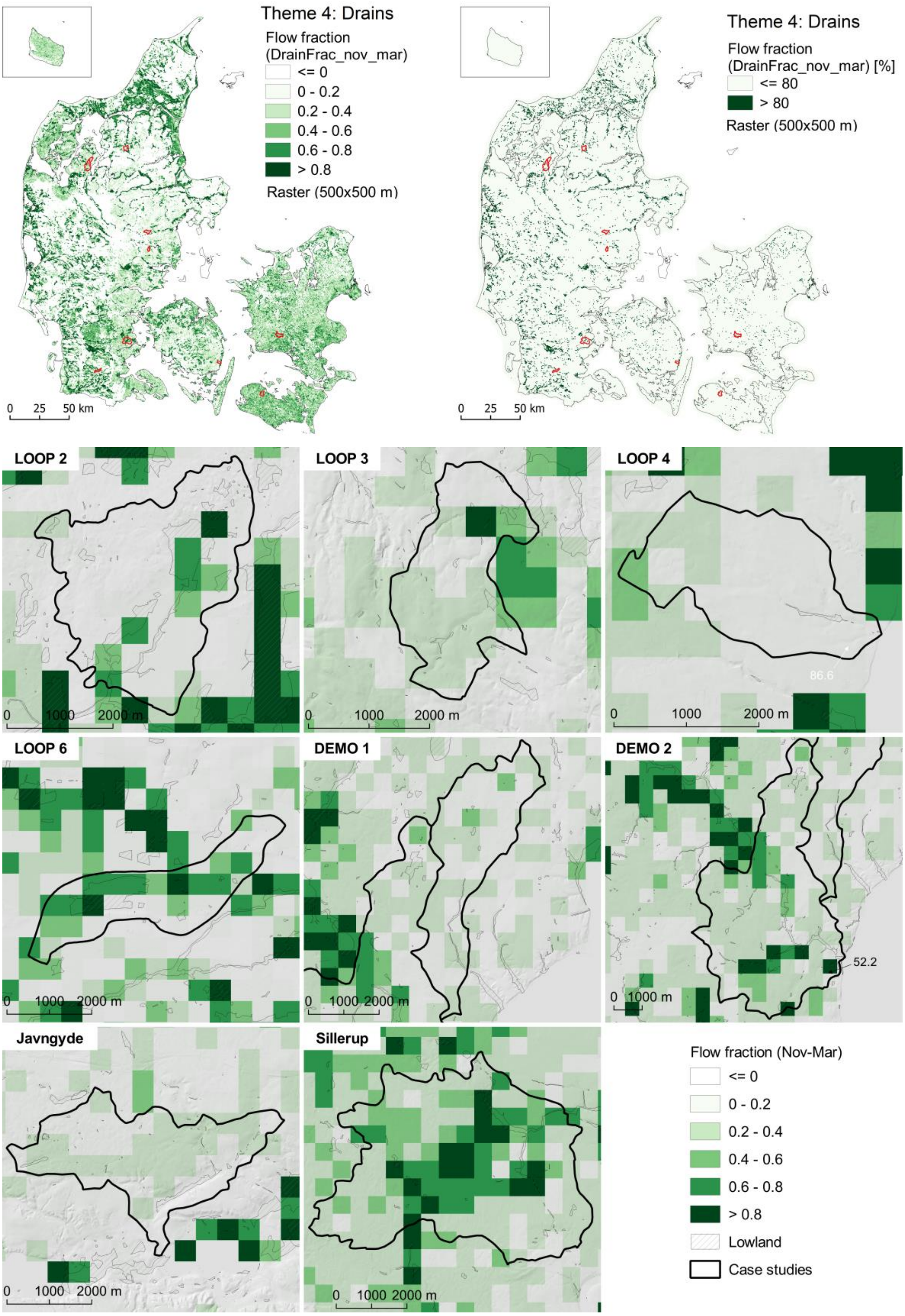

Figure 23 *Simulated flow fraction through drains and ditches (Højberg et al., 2021): left – 6 classes, right – binary. On the case studies maps, the transparent terrain shadow (DHM, Kortforsyningen) gives a greyish tint to the lightest categories.*

Appendix 3: Agricultural area

To calculate the percentage of agricultural area at the ID15 catchments (**Figure 24**), field-level data were used, where the type of crops or agricultural practice was available for each field in Denmark. The fields related to reforestation, wetlands, or green houses were excluded, as well as all codes (activities) shown in **Table 8**, as those are not relevant to the MapField concept.

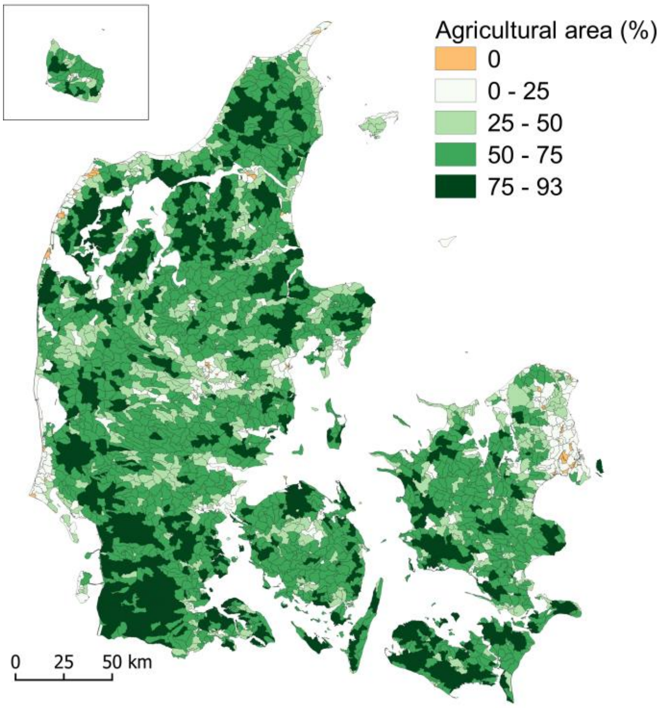

Figure 24 *Percentage of agricultural area within each ID15 catchment (v.2.2) based on field-scale inventory.*

Table 8 *Codes excluded from the agricultural area calculation*

Code	Afgrøde (Crop yield)
271	Rekreative formål
311	Skovrejsning på tidl. landbrugsjord 1
312	20-årig udtagning
313	20-årig udtagning af agerjord med frivillig skovrejsning
316	20-årig Udtagning med fastholdelse, ej landbrugsareal
317	Vådområder med udtagning
318	MVJ ej udtagning, ej landbrugsareal
319	MFO-brak, Udtagning, ej landbrugsareal
321	Miljøtiltag, ej landbrugsarealer
322	Minivådområder, projekttilsagn
499	Lukket system
575	Skovrejsning (privat) ? kulstofbinding og grundvandsbeskyttelse
576	Skovrejsning (statslig) - forbedring af vandmiljø og grundvandsbeskyttelse
577	Skov med biodiversitetsformål
578	Skovrejsning (privat) - forbedring af vandmiljø og grundvandsbeskyttelse
580	Anden skovdrift
581	Skovdrift med fjernelse af ved

Code	Afgrøde (Crop yield)
585	Skovrejsning i projektområde, som ikke er omfattet af tilsagn
586	Offentlig skovrejsning
587	Skovrejsning på tidl. landbrugsjord 3
589	Bæredygtig skovdrift
590	Bæredygtig skovdrift i Natura 2000-område
591	Lavskov
903	Lysåbne arealer i skov

Appendix 4: Primary data availability

The four primary data sources used in geological, hydrogeological, and hydrogeochemical modelling in Denmark are:

- Lithological information from all available boreholes
- Geophysical data
- Surface geology map (geology at dept 1m, soil-parent material)
- Sampling points with redox data (samples including NO_3, O_2, SO_4, Fe analysis)

Figure 25 visualizes the availability of primary data at each ID15 catchment. These maps were based on the old delineation of the ID15 catchments (Højberg et al., 2015a, 2015b) and were not revised as they are not used directly in the prioritization tool. However, they could still provide a useful overview nationwide, but if the information needs to be used together with the rest of the data presented in this report, this should be done with caution. Some of the polygons have changed substantially, so the ID numbers of the catchments from the two versions – the old (Højberg et al., 2015a, 2015b) and the new (Højberg et al., 2021) – are not always compatible.

Here, we provide some more information on the data sources and data-handling used for producing the maps on ***Figure 25***.

Borehole lithology data

The dataset including boreholes with lithological descriptions were downloaded from Jupiter on 11 Feb 2021. Only the boreholes fulfilling the following conditions were included in the download:

- depth of minimum 10 m AND
- more than 4 lithology samples AND
- with available UTM-coordinates
- not confidential

Additional columns were included in the data download, in case more sophisticated weighting and rating system is used at a later stage of the tool-development. For example, there is information on who did the description of lithological samples, number of samples sent to the well-sample lab, purpose of the well, date when the well-establishment started and ended, and date of reporting to Jupiter.

Two different calculations are done on ID15 catchment scale to account for the data availability (**Figure 25**):

- density of boreholes (number per km^2)
- cumulative well-length per km^2 (m per km^2)

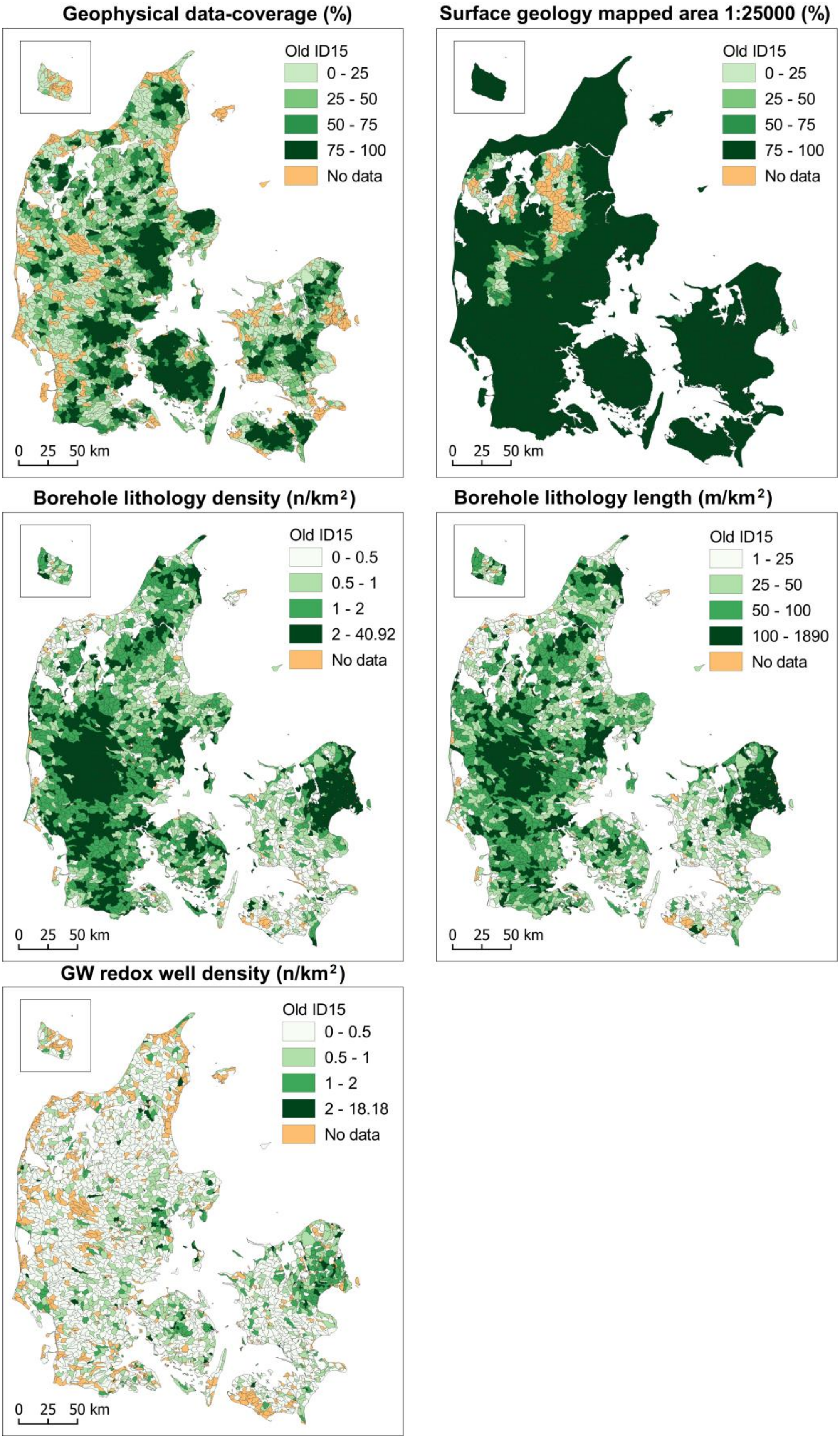

***Figure 25** Maps showing the primary data coverage*

Availability of geophysical data

The purpose is to determine the areal percentage of each ID15 catchment surveyed by geophysical data, and to identify data gaps.

The following geophysical methods were selected due to their widespread areal coverage:

- PACES/PACEP – pulled array continuous electrical sounding method; PACES is collected in 8 electrode configurations, while PACEP is older and it is collected in 3 electrode configurations.
- MEP – multi electrode profiling (MEP) is collected with two types of electrode configurations – Gradient (newer, more dense sampling), and Wenner (older).
- TEM – ground-based transient electromagnetic method with single soundings, collected with several different systems
- SkyTEM – airborne transient electromagnetic method.

Information about the methods and their use in Denmark is provided in the documentation report for the Nitrate state of Danish groundwater bodies (Thorling et al., 2019) as well as in Gravesen et al. (2014).

The input data (point shape files for each geophysical method) were extracted from GERDA for the Nitrate state project (Thorling et al., 2019) and include all data available until 24 May 2019.

The data coverage was assessed based on polygons delineated around the data points for each of the selected methods (***Figure 26***). The polygons were delineated with the ArcGIS tool “Aggregate points” around clusters of points with a maximum distance of 800 m between the points.

It is expected that the polygons for different methods will overlap spatially. Historically, when TEM was used in the 1990s and early 2000s, PACES was collected in the same areas to obtain information on the full depth profile from surface to up to ca. 150 m depth. PACES and SkyTEM also overlap, as PACES was also applied for the first 8-10 year of SkyTEM (2003–ca. 2013). Therefore, PACEP/PACES and TEM/SKYTEM will typically overlap spatially in some areas. There might as well be some overlap between ground-based TEM measurement and SkyTEM surveys as smaller areas with sparse TEM sounding may have been included in areas covered by larger SkyTEM surveys. Even though MEP has typically been collected as the only method in an area, it has also been collected less intensely in combination with TEM/SkyTEM. For this analysis, however, we focus on the combined extend of the different geophysics data without distinguishing between methods.

The four polygon shapefiles (***Figure 26***) were merged and dissolved (***Figure 27***), and the QGIS tool “Overlap analysis” was used to calculate the area and percentage cover of ID15 catchments.

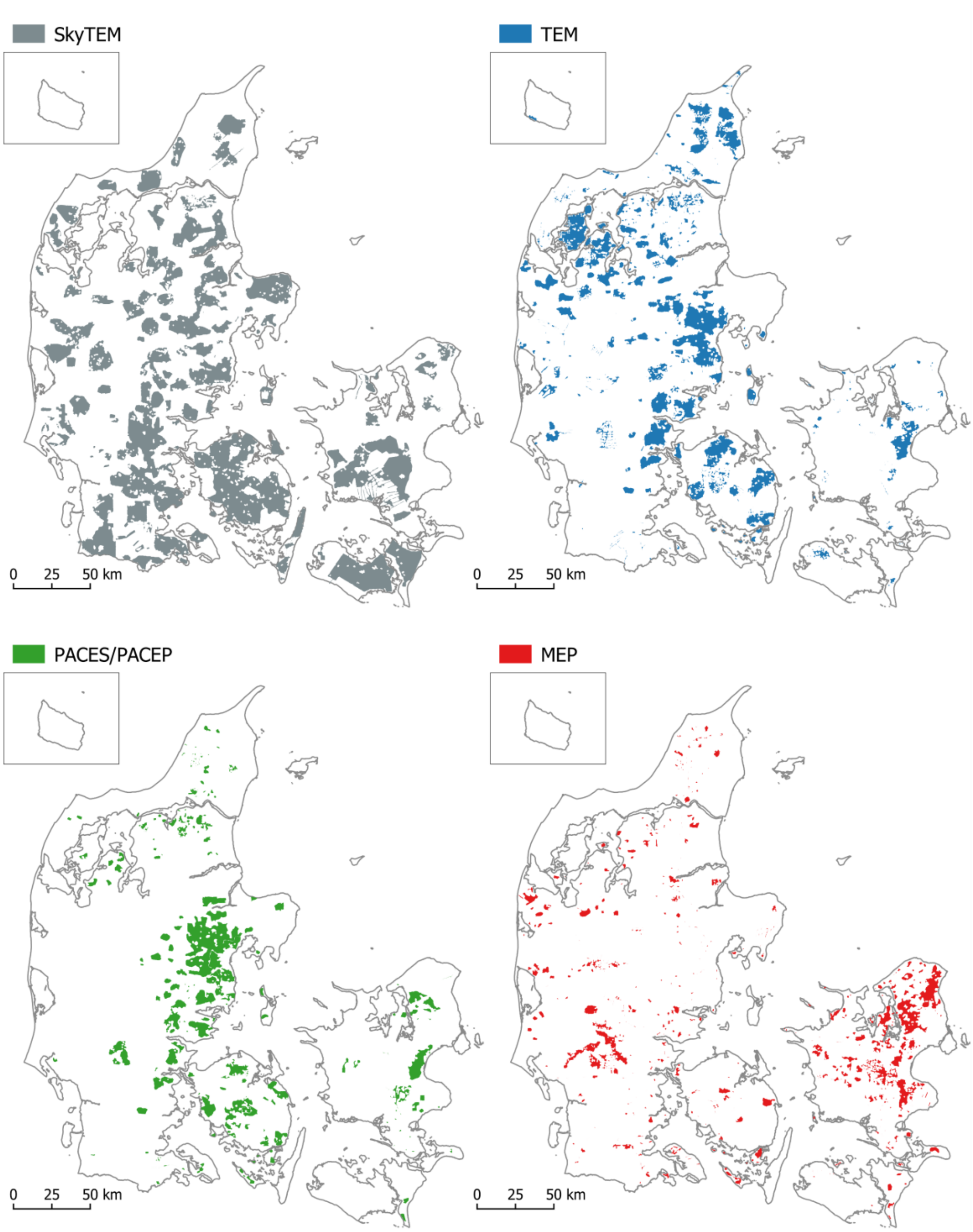

Figure 26 *Polygons delineated around the survey points for each geophysical method*

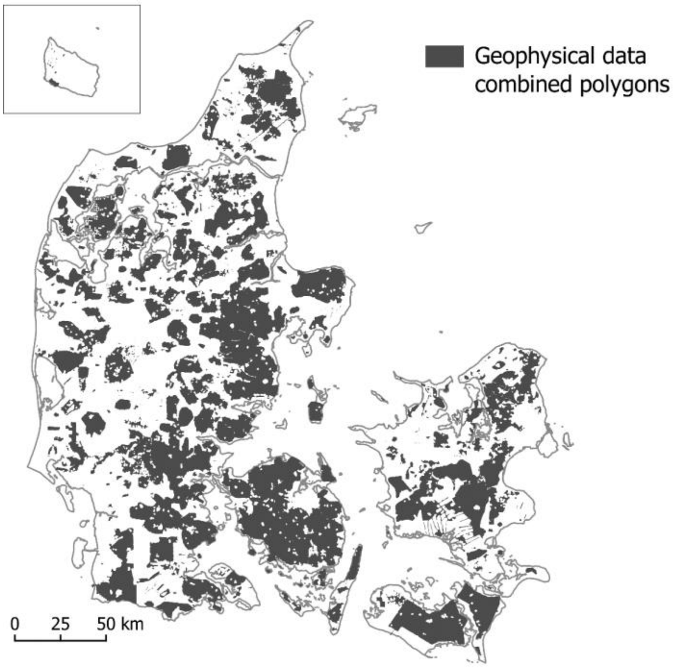

Figure 27 Merged and dissolved polygons from **Figure 26** showing the data coverage by the selected geophysical methods

References for Appendix 4

Gravesen, P., Balling, I.M., Vignoli, G., Klint, K.E.S., Brüsch, W., Nilsson, B., Larsen, C.L., Juhler, R., Rosenbom, A.E., 2014. Vurdering af mulighederne for udpegning af pesticidfølsomme lerområder (SFO-ler) på grundlag af eksisterende data. Udarbejdet for Naturstyrelsen. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2014/2, pp 302. http://geus.net/geus_rap_2014_2.pdf

Højberg, A.L., Windolf, J., Børgesen, C.D., Troldborg, L., Tornbjerg, H., Blicher-Mathiesen, G., Kronvang, B., Thodsen, H., Ernstsen, V., 2015a. National kvælstofmodel, Oplandsmodel til belastning og virkemidler – Metode rapport. Revideret udgave september 2015. GEUS and AU, p.111. https://www.geus.dk/media/7744/national-kvaelstofmodel-oplandsmodel-til-belastning-og-virkemidler-sep2015.pdf

Højberg, A.L., Windolf, J., Børgesen, C.D., Troldborg, L., Tornbjerg, H., Blicher-Mathiesen, G., Kronvang, B., Thodsen, H., Ernstsen, V., 2015b. National kvælstofmodel, Oplandsmodel til belastning og virkemidler – Bilag. Revideret udgave september 2015. GEUS and AU, p.402. https://www.geus.dk/media/7745/bilag-til-national-kvaelstofmodel-oplandsmodel-til-belastning-og-virkemidler-sep2015.pdf

Thorling, L., Møller, I., Nilsson, B., Sandersen, P., Troldborg, L., 2019. Dokumentationsrapport, Nitrattilstand for grundvandsforekomster, metodeudvikling. Miljøstyrelsens projekt "Udvikling af metode for relevante undersøgelser for vurdering af nitratpåvirkning af grundvandsforekomsterne (GVF) – Leverance 7". GEUS Rapport 2019/6, p.164. https://mst.dk/media/186799/12-nitrattilstand-for-grundvandsforekomster-metodeudvikling-dokumentationsrapport-af-geus-for-miljoestyrelsen-2019.pdf

Appendix 5: Lowland areas

The lowland data (polygon shapefile "lavbund") were downloaded from DCA (https://dca.au.dk/forskning/den-danske-jordklassificering/). The lowland areas have been mapped based on GMI map (scale 1: 20,000, after 1990s), including meadows, bogs, and marshes (from the GMI map), and supplemented with the landscape map from DCA, where the elements marshy, drained/dammed areas, Littorina and the younger marine sediments (from the Yoldia sea) are also included.

The percentage of lowland area coverage for each ID15 catchments polygons was calculated (**Figure 28**).

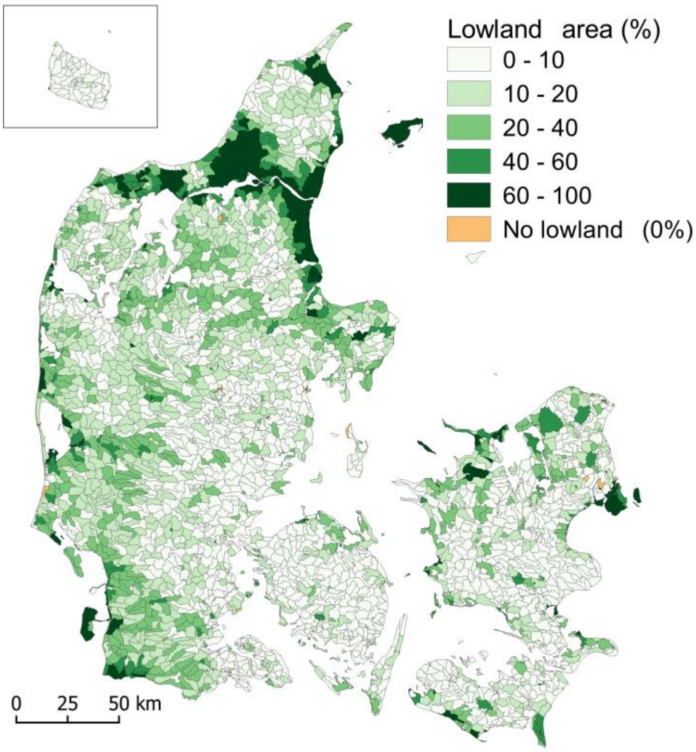

Figure 28 *Percentage of lowland area within each ID15 catchment (v.2.2)*

Appendix 6: List of ID15 catchments and their characteristics

The input data at ID15 level, the rated themes, and the results at Steps 1-3 are exported as:

- an xlsx file – “Final_ID15new_AppendixTable.xlsx”
- a shape file – “Final_prioritization_tool_ag_lowlands.shp”

The files are stored in the folder:
\\netapp2p\Grundvand\PROJEKTER\MapField\Prioriteringsværktøj\0_FINAL_PRIORITIZATION_TOOL

There are 3351 rows and the following 20 columns:

Column name	Unit	Explanation
ID	-	Identification number of ID15 catchments v.2.2 from *Højberg et al. (2021)*
Area_km2	km^2	Total area of ID15 catchments
AreaHa	ha	Total area of ID15 catchments
AgAreaHa	ha	Agricultural area
AgAreaPCT	%	Agricultural area in percentage
LowlandHa	ha	Lowland (riparian zone) area
LowLaPCT	%	Lowland (riparian zone) area in percentage
GeoCmpl	-	Geological complexity class: H – high, MH – moderate to high, LM – low to moderate, L – low
GeoCpct	%	Area within the ID15 with this class of geological complexity in percentage
T1_Geol	-	Theme 1: Geology (score)
RedMedM	m	Median difference between FRI and AB
T2_Red	-	Theme 2: Redox (score)
RedSurf	%	N-retention in surface waters from *Højberg et al. (2021)* in percentage
T3_NSurf	-	Theme 3: Surface N-retention (score)
N_DrnFrac	%	Fraction of N-transport through drains and ditches, calculated based on *Højberg et al. (2021)* in percentage
T4_Drain	-	Theme 4: Degree of drainage (score)
T5_Dem	-	Theme 5: N-reduction demand (score)
Step1	-	T1 x T2
Step2	-	Step 1 x T3 x T4
Step3	-	Step 2 x T5