National scale groundwater assessments in Denmark using machine learning and hybrid modelling

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Evolution of groundwater action plan

Artificial intelligent and groundwater gestion

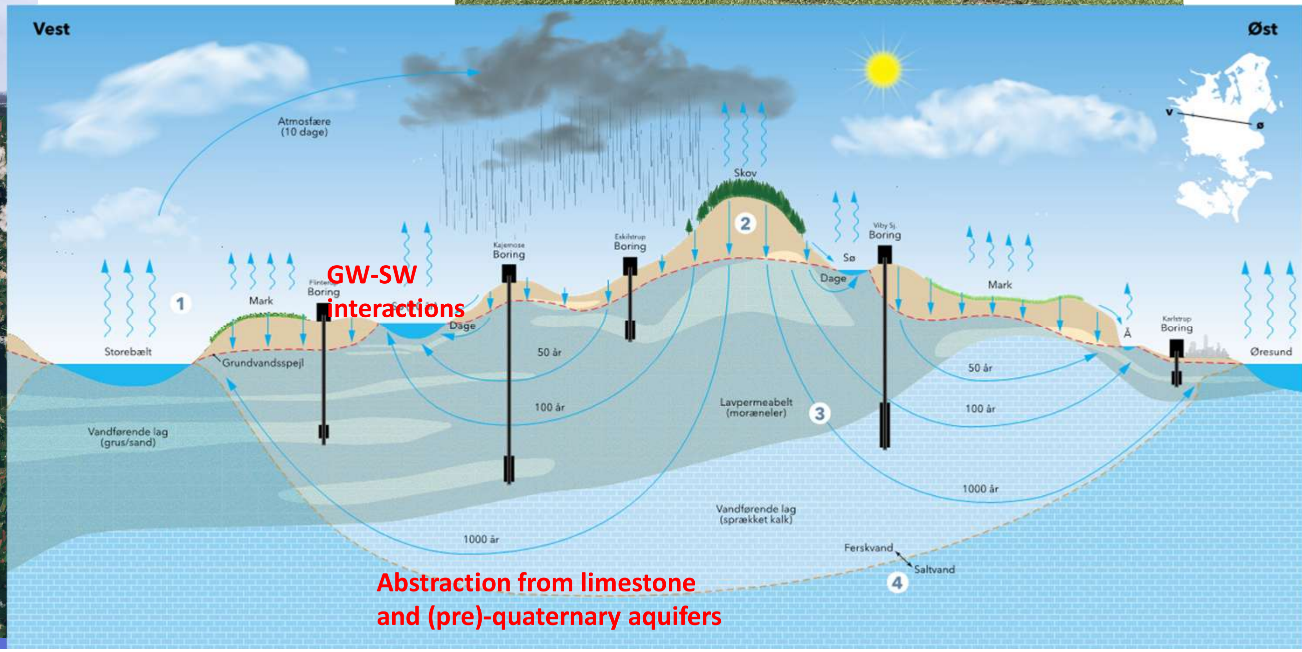
G E U S

Content

Modelling to support national-scale assessments of

1) Groundwater **quantity**
2) Groundwater **quality**

→ **Understanding pressures and creating a foundation for science-based decision making**

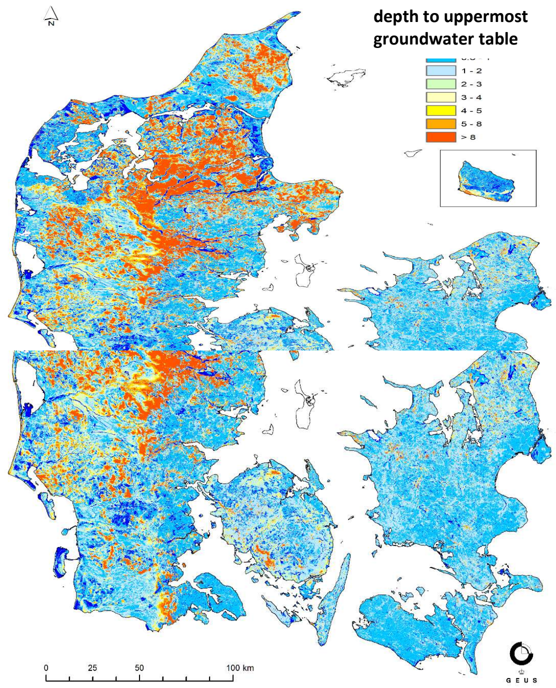


Groundwater Quantity

Vision:

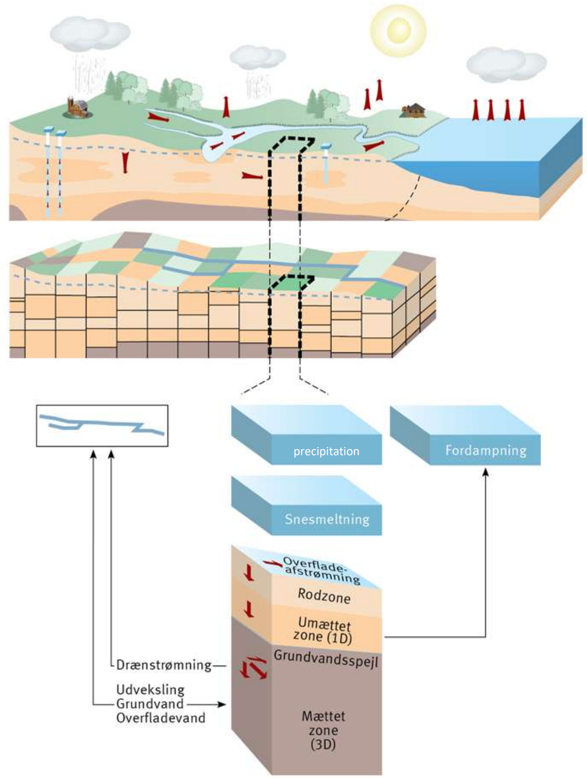
Unbiased & temporally dynamic & high-resolution depth to groundwater for historic & current & future conditions

The National Hydrological Model of Denmark (DK-model)



The DK-model is an **integrated, distributed hydrological model**. It serves as basis for

- Water resource assessments
- Nutrient transport modelling
- Monitoring of the hydrological cycle and early warning
- Climate change impact assessments
- Local detailed models
- …



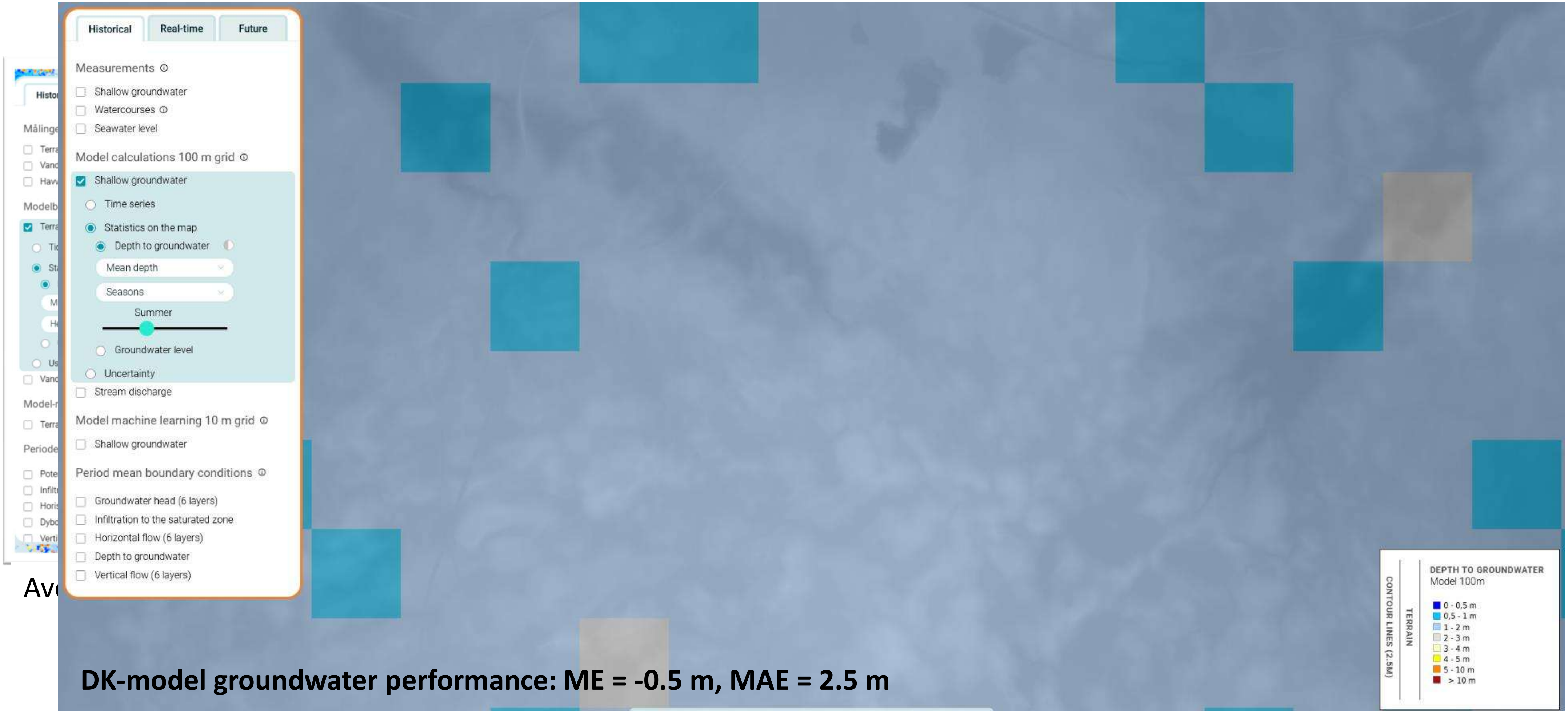
~43.000 km^2
Horizontal: 100 m and 500 m grid
Vertical: variable 9 – 22 computational layers
Daily timestep
Historic, **real-time with forecast** and climate models

MIKE SHE code

- **3D-FD groundwater** flow model
- **Streamflow routing** module
- Couples surface water – groundwater
- Coupled **1D unsaturated zone**/ET module
- Range of water management option

Stisen et al. (2019)

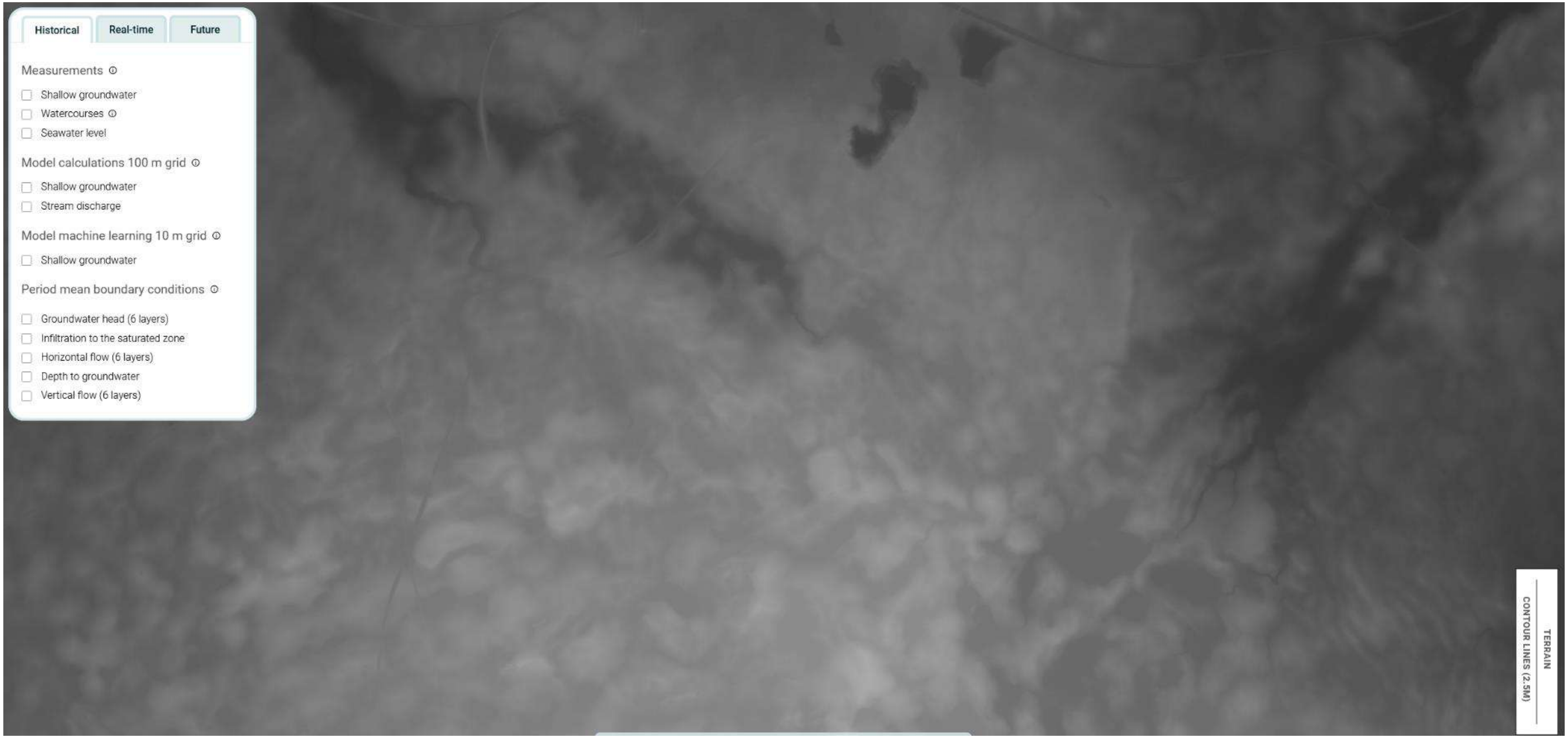
100 m data from DK-model: Dynamic



DK-model groundwater performance: ME = -0.5 m, MAE = 2.5 m

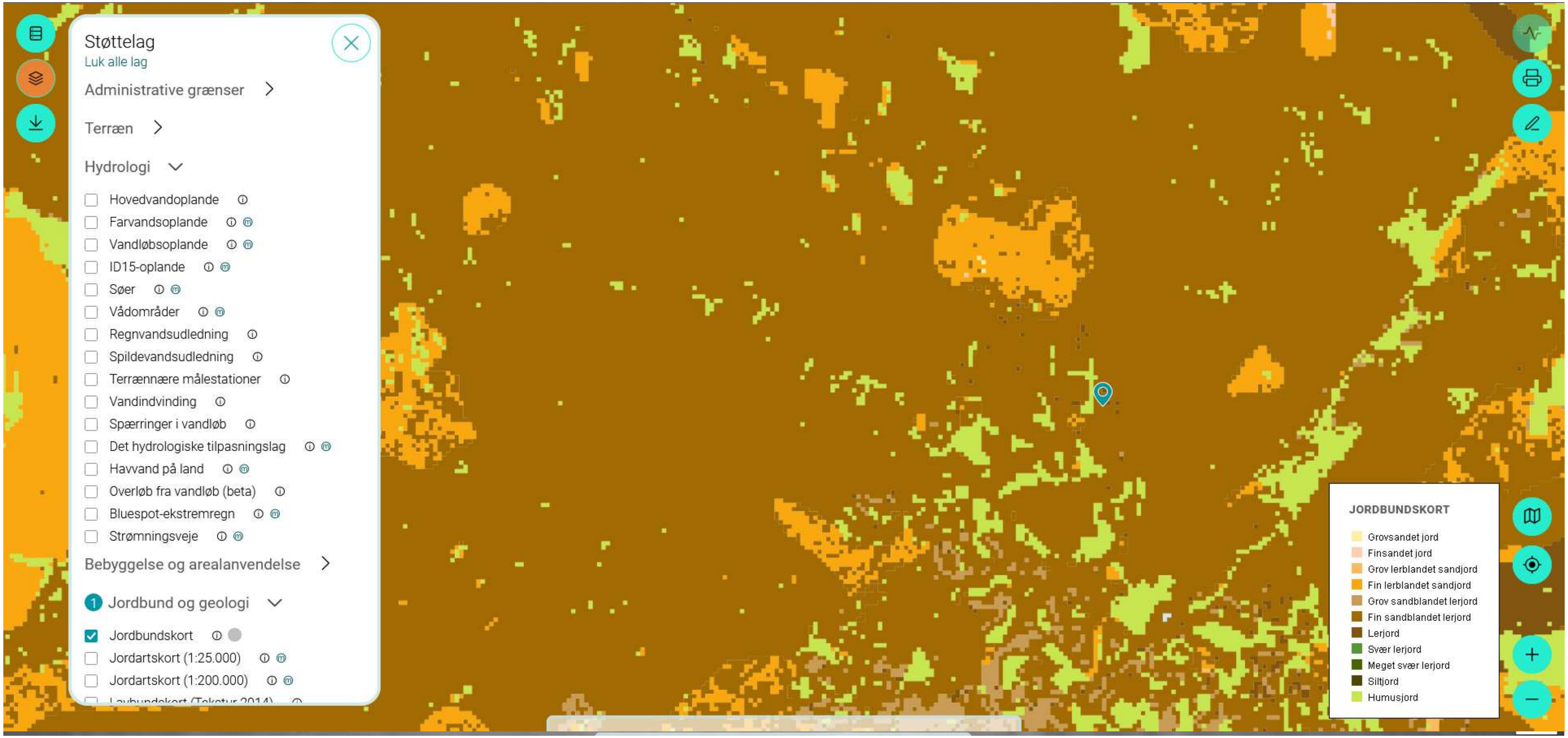
From 100 m to 10 m – explanatory variables at high resolution

Topography

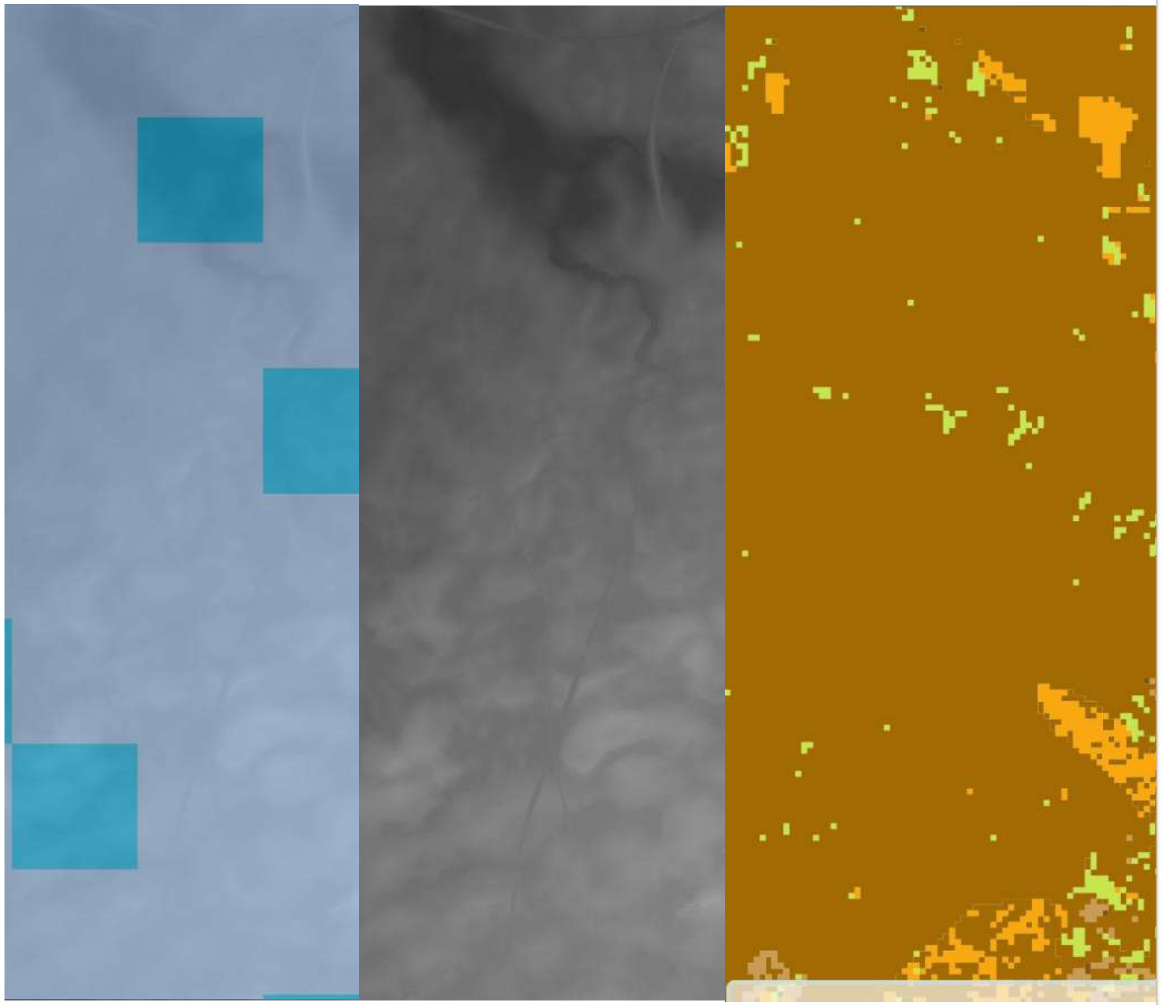


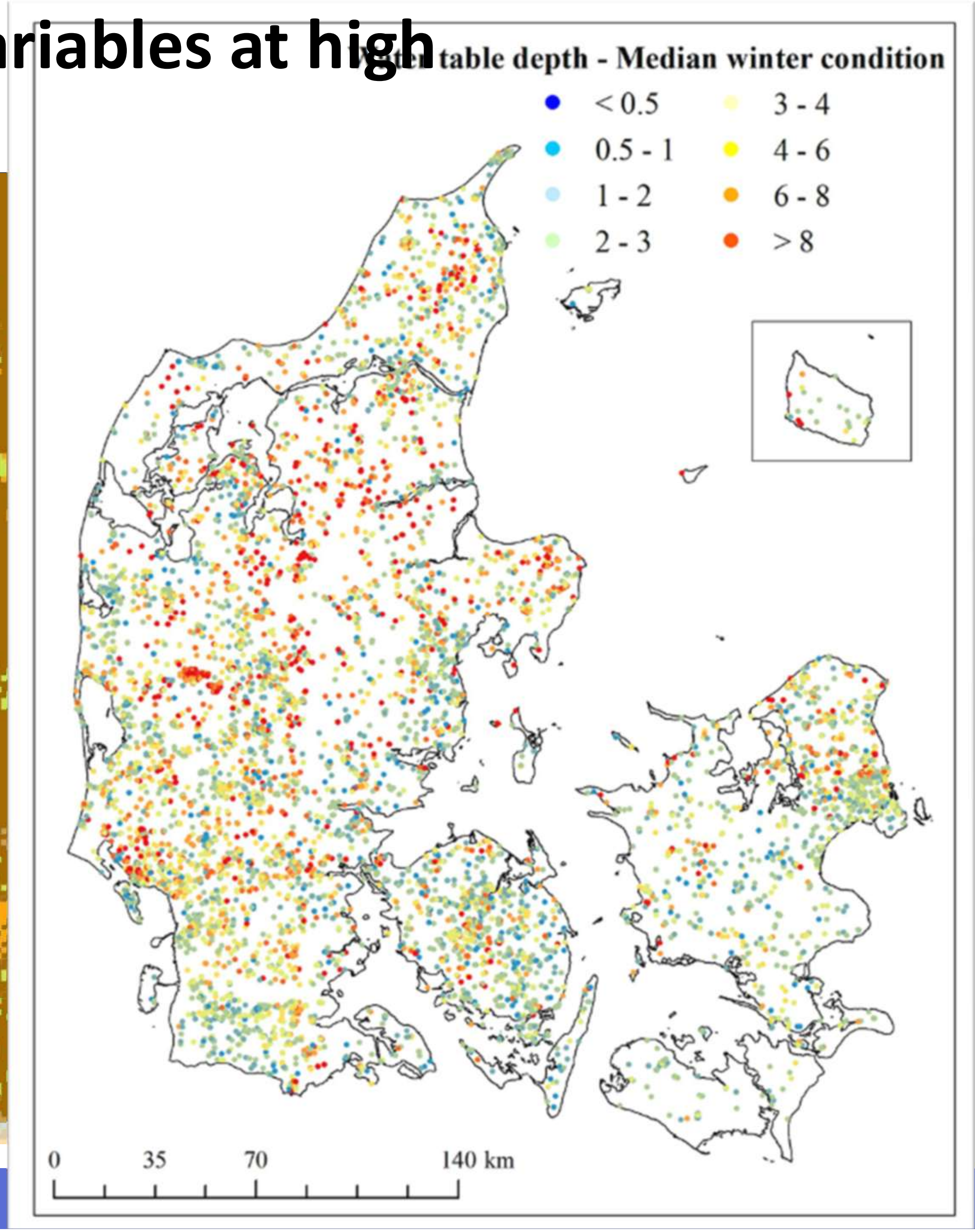
From 100 m to 10 m – explanatory variables at high resolution

Soil Type



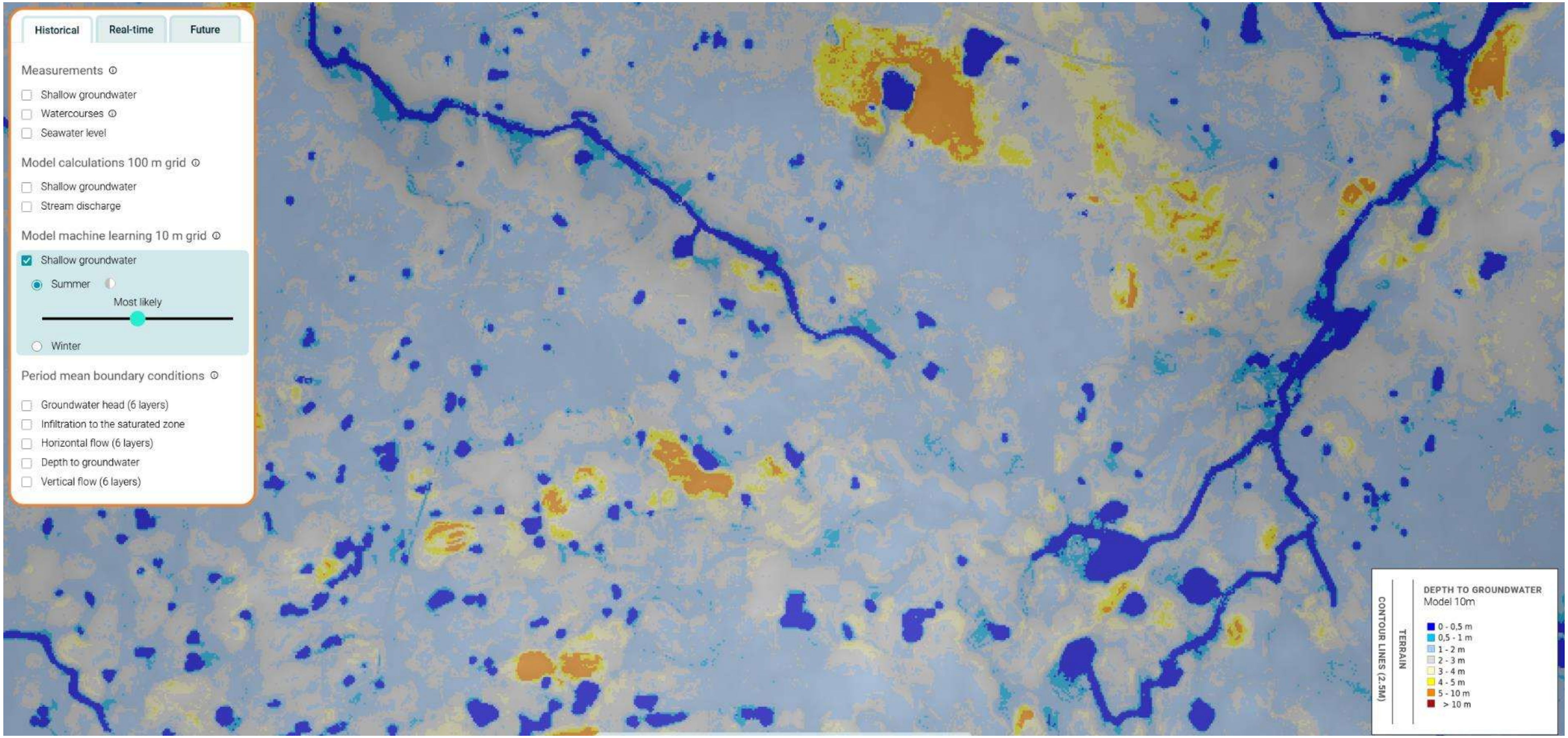
From 100 m to 10 m – explanatory variables at high resolution



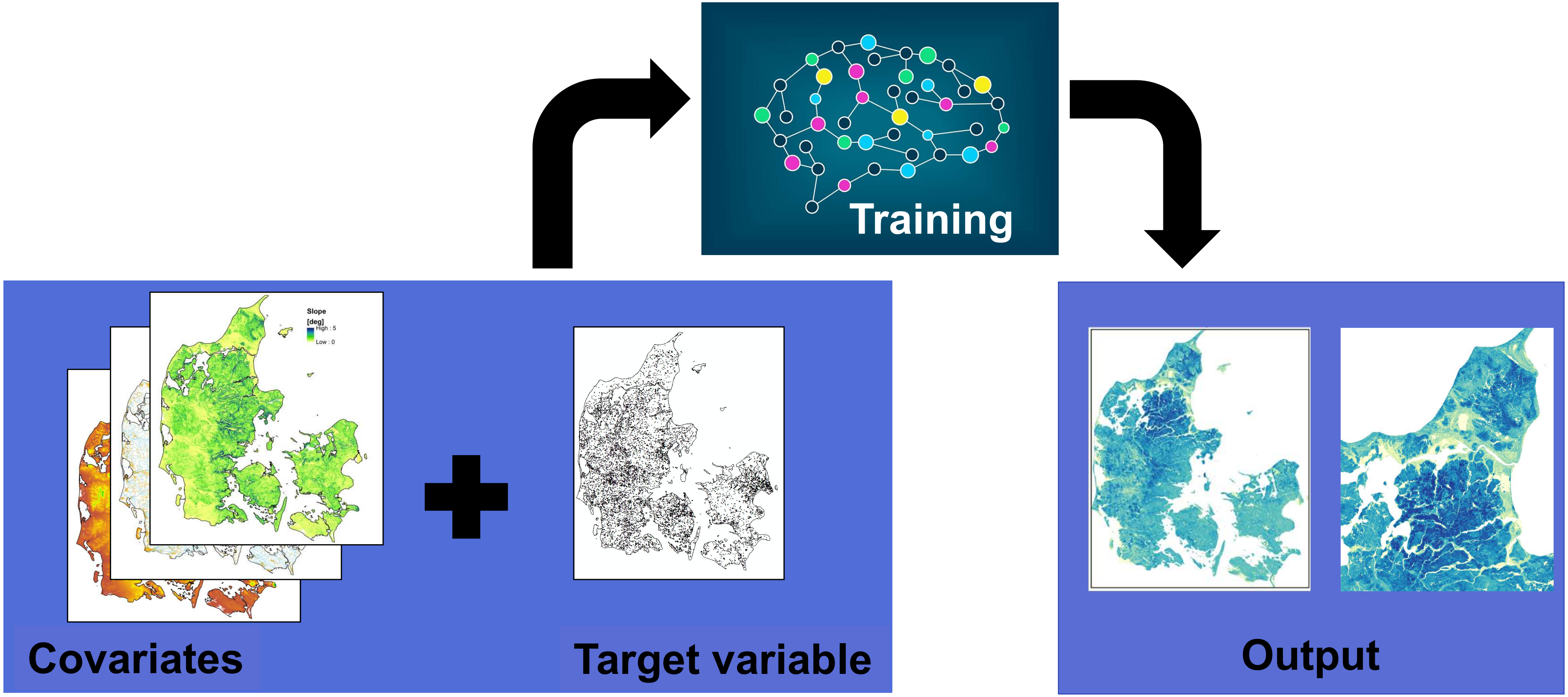


From 100 m to 10 m

Depth to uppermost groundwater, summer, **10m ML**



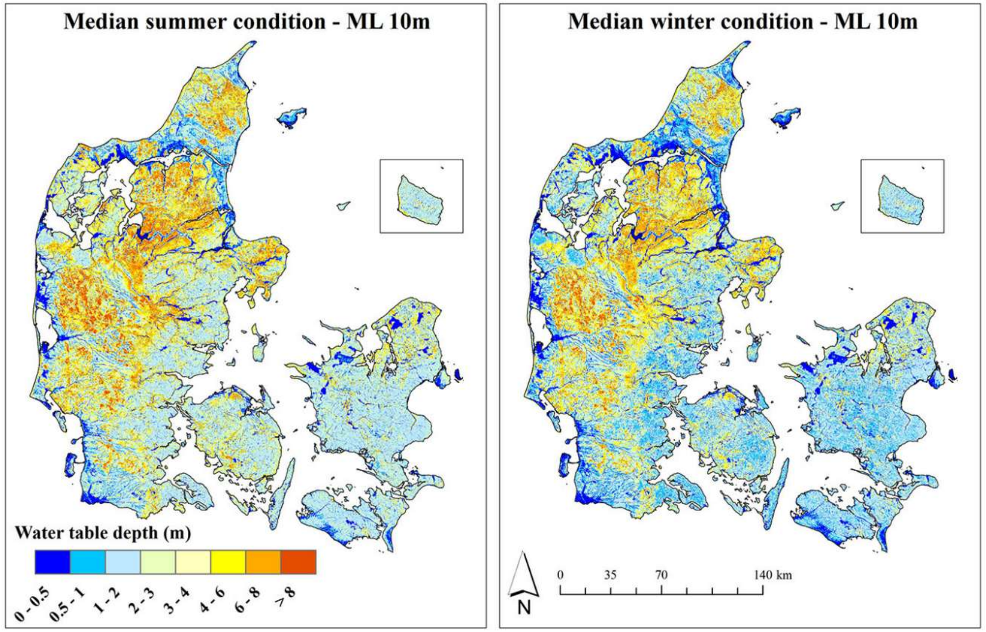
Geospatial ML modelling

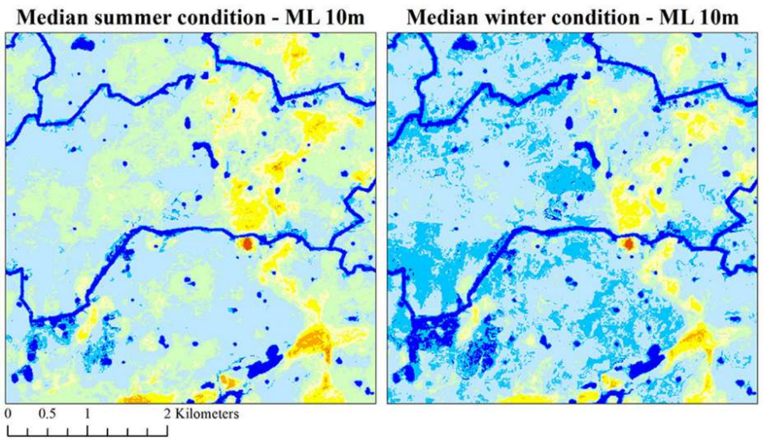


Geospatial ML modelling

- Steady state **water table depth** simulated with decision tree algorithm (gradient boosting)
- Linking point observations with high-resolution covariates

HIP: National scale at 10 m - WTD for typical summer and winter conditions





Koch et al. (2021)

Hybrid Modelling

- Hybridization of process-based model (**PBM**) and machine learning (**ML**)
- Objective: Enhance performance of process-based model
- **Solution 1:** Use **PBM** as input to **ML**
- **Solution 2:** Use **ML** to model residuals of **PBM** model

→ Post-processing of PBM model

What we do not do: Emulation of PBM, physics informed ML

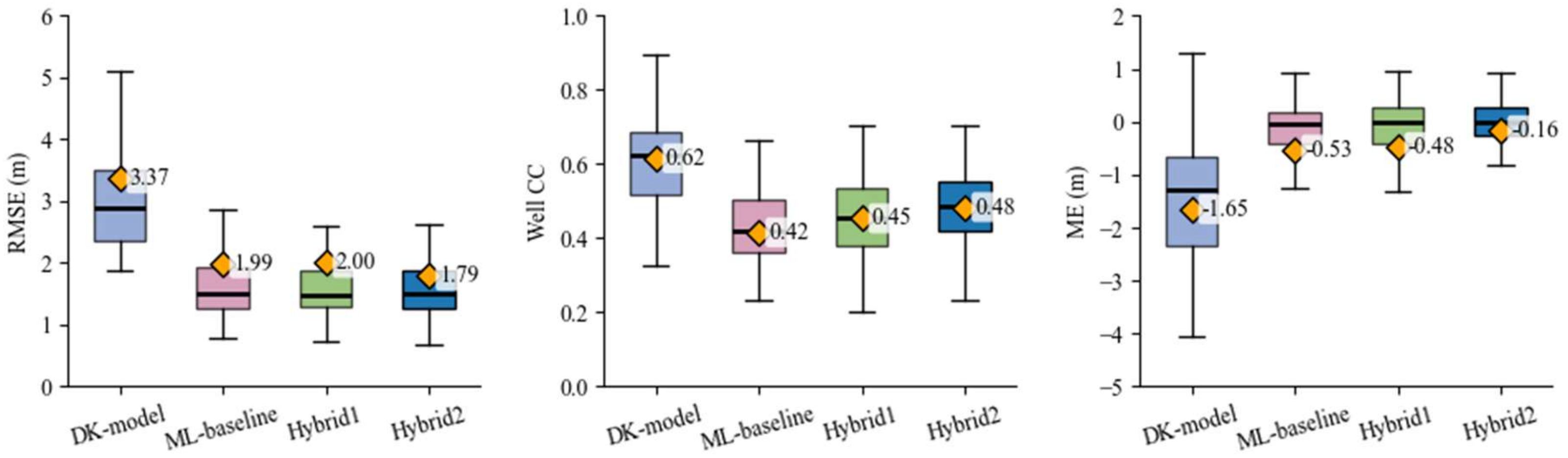
Application

Groundwater depth modelling combing DK-model and decision trees

Daily and scale flexible

Groundwater Hybrid

- How well does the hybrid model extrapolate to unseen wells?
- Wells were held out by well cluster (N = 50) → no shared wells between training and test sets.
- Hybrid models show improved accuracy (RMSE & ME) in water table depth estimation.
- Temproal dynamics are currently not improved (correlation coefficient, CC)

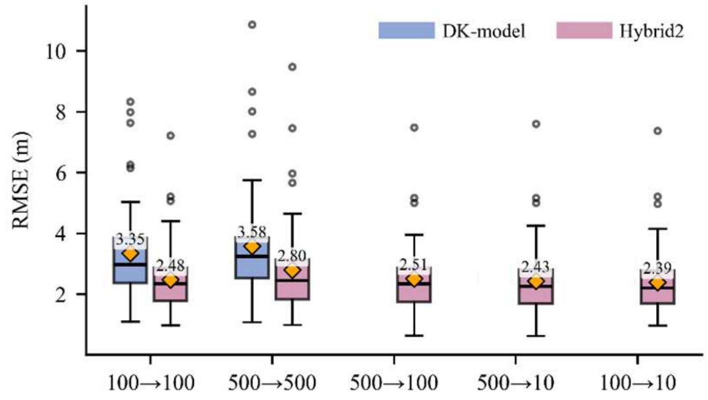


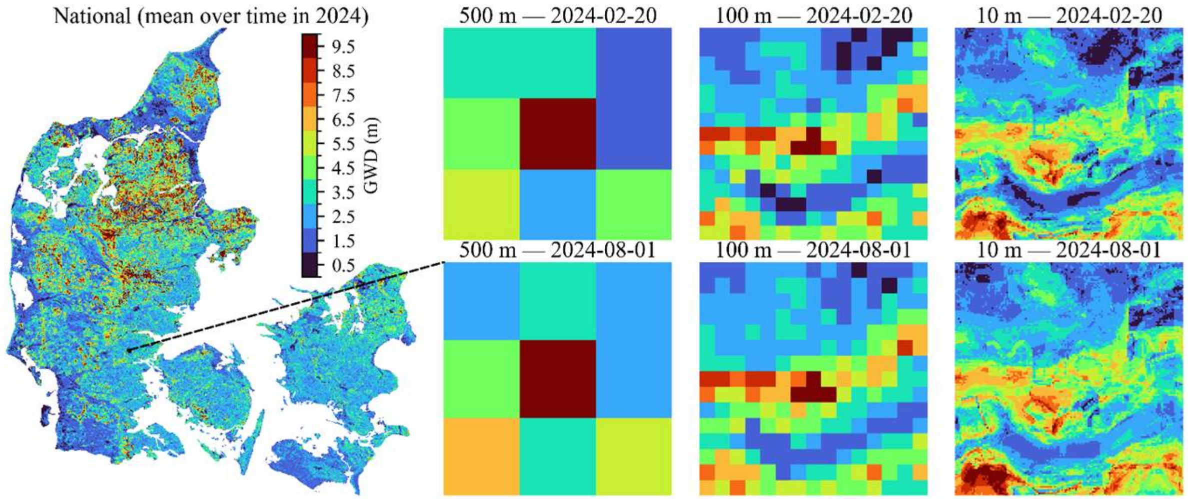
- **ML-baseline**: Observed WTD, no simulations as input
- **Hybrid 1**: Observed WTD, simulations as input
- **Hybrid 2**: Residuals (Observed WTD - Simulated WTD)

Liu et al. (2025)

Groundwater Hybrid

- How well does the model perform across scales?
- The model was trained on coarse-resolution data (100 m or 500 m)
- It was then used to predict WTD at higher resolution (10 m)
- Predictions at 10 m resolution may outperform those at coarser scales





Liu et al. (2025)

Groundwater Quantity

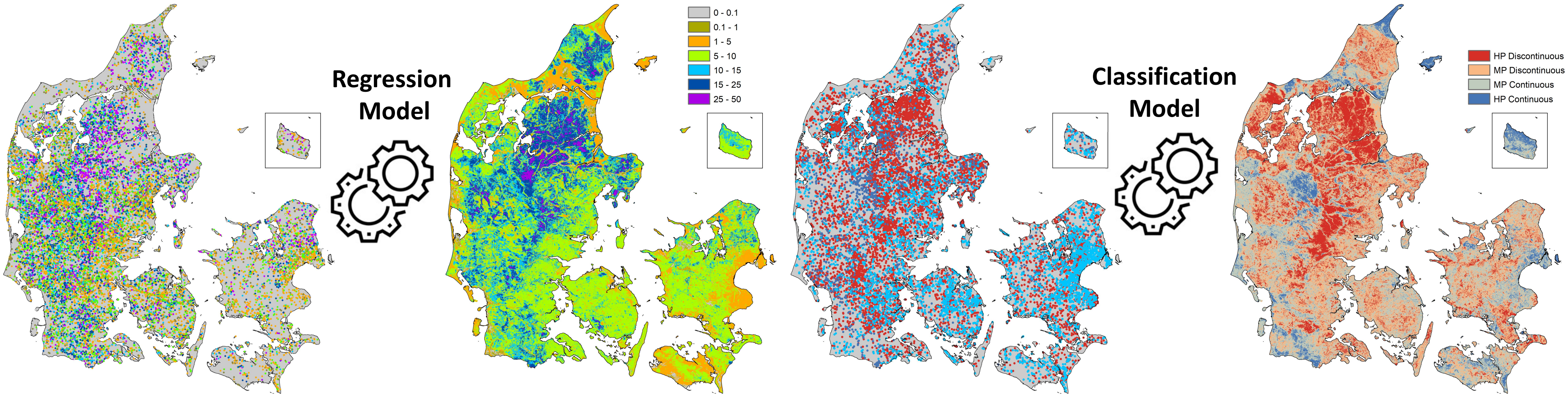
Vision:

Spatially consistent overview of contaminants and redox conditions

Groundwater Redox Conditions

1) First Redox Interface
Sediment Color

2) Redox Complexity
Water Chemistry



Gradient Boosting with Decision Trees

27 Covariate Maps: Hydrogeology, Topography, Lithology, etc.

K-fold Cross Validation

Feature Importance Analysis: SHAP

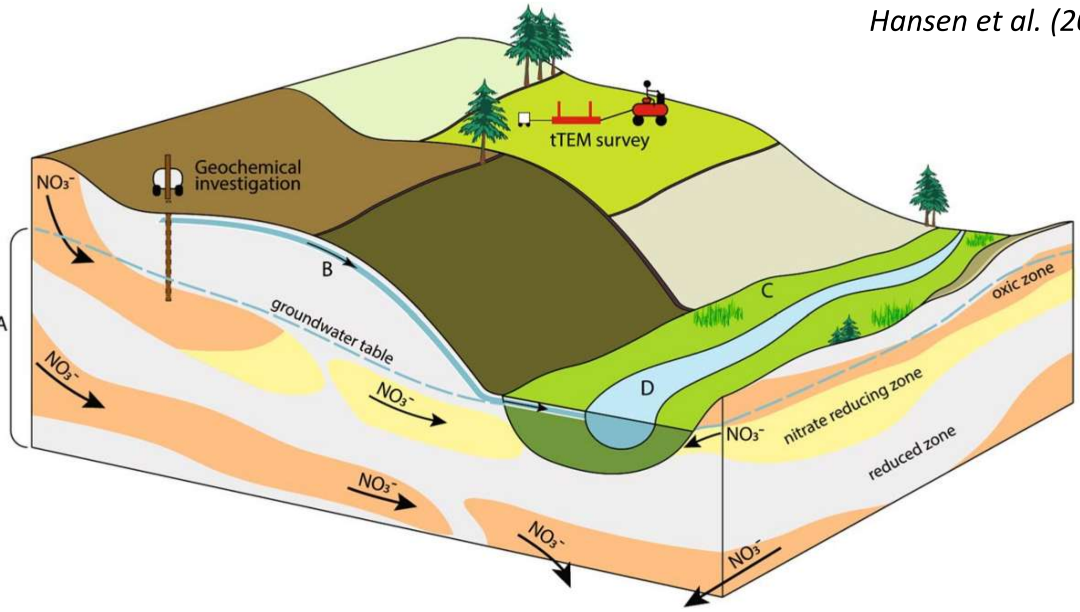
Uncertainty Quantification: Quantile Regression

Koch et al. (2024)

Motivation

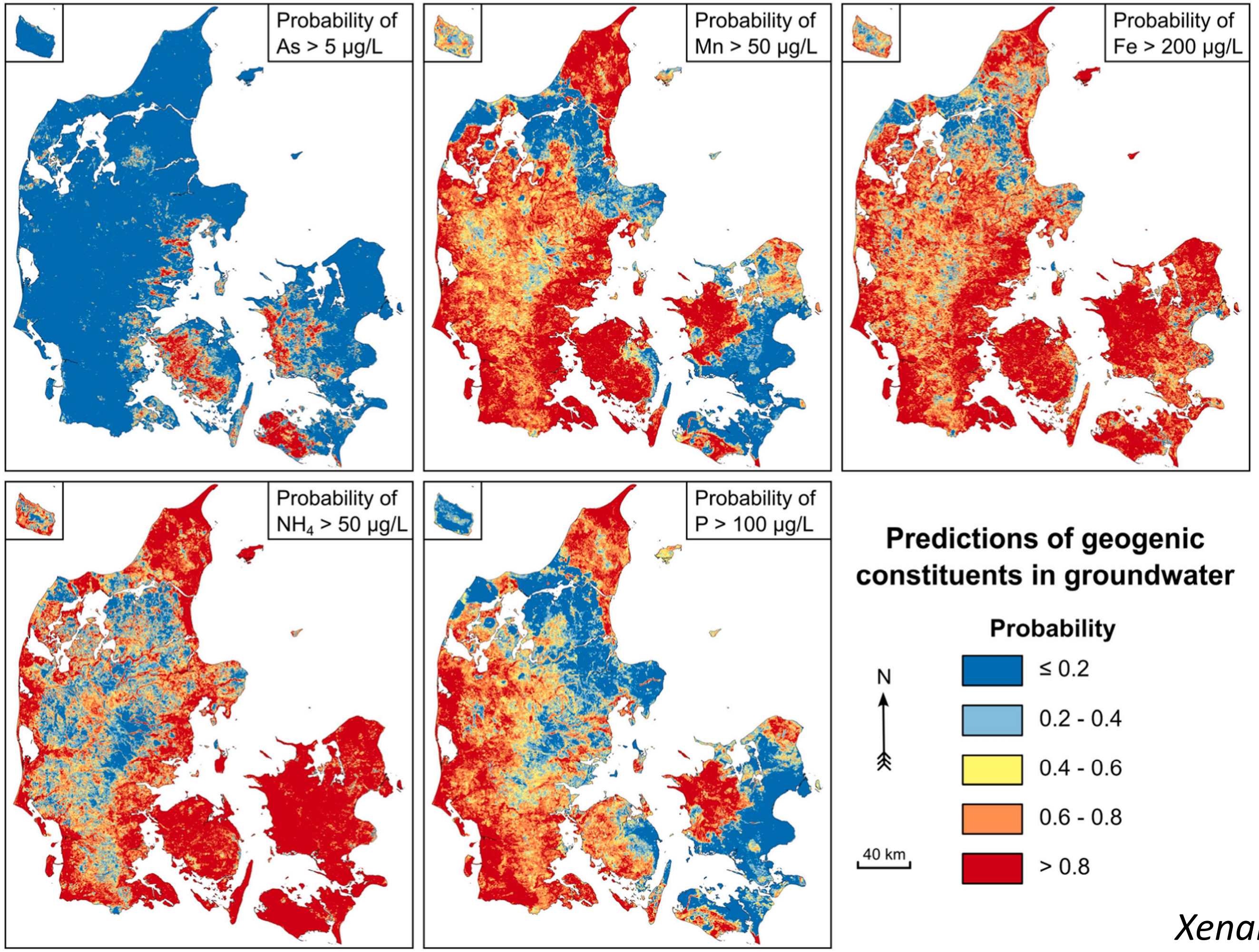
- Groundwater redox conditions (aerobic/anaerobic) modulate a wide range of biogeochemical processes
- Investigate the fate of nitrate → where does denitrification take place in groundwater?
- We focus on the identification of the **first redox interface**, i.e, bottom of uppermost oxic zone
- We develop a concept for mapping **redox complexity**, i.e. presence or absence of multiple redox interfaces

Hansen et al. (2024)



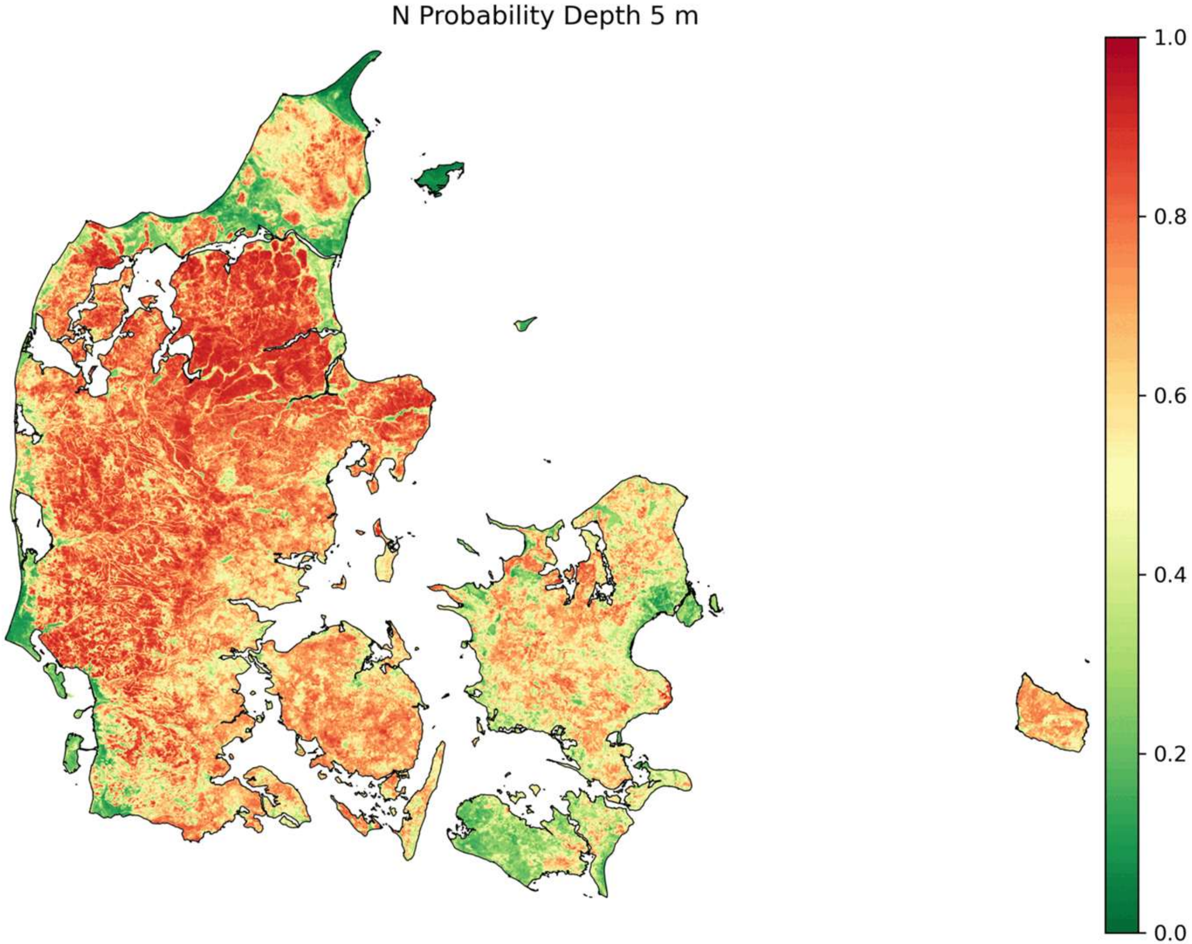
Redox knowledge in use:
- Water quality assessments – Water Framework Directive
- Agricultural regulation - areas vulnerable or robust to nitrate leaching

Geogenic Contaminates in Groundwater



Xenakis et al. (2026)

Depth Dependent Nitrate Contamination



Thank you for your attention!

Koch, J., Gotfredsen, J., Schneider, R., Troldborg, L., Stisen, S., & Henriksen, H. J. (2021). High Resolution Water Table Modeling of the Shallow Groundwater Using a Knowledge-Guided Gradient Boosting Decision Tree Model. *Frontiers in Water*, 81.

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