# Mapping and protection of groundwater – Experiences and ways ahead

LTH & Online 14 November 2023

Lund University
LTH Faculty of Engineering
SIWI Swedish Water House

# Agenda

- Welcome and intro about the Multi-stakeholder Group on Groundwater – **Malin Wennerholm**, SIWI Swedish Water House
- Introduction about the importance of groundwater as a resource – **Torleif Dahlin**, LTH/Lund University
- Overview of the background and implementation of the national groundwater mapping of Denmark – **Frederikke Storm Hansen**, Miljøministeriet Danmark

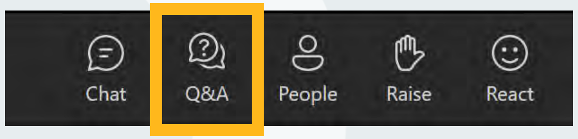
*(Short break)*

- Developments after the completion of the national groundwater mapping – **Esben Auken**, Aarhus Geoinstruments/Aarhus University
- Overview of groundwater mapping with SkyTEM and other methods in Sweden – **Peter Dahlqvist**, SGU (Geological Survey of Sweden)
- Combined DCIP-MRS for mapping hydraulic properties of the ground – **Tina Martin**, Lund University

*12:15-13:15 Lunch (For onsite participants only)*

- 13:15-14:00 Discussion on needs and ways ahead

Post your questions in the Q&A function!




Moderated by **Torleif Dahlin, LTH**

# SIWI Swedish Water House

- Housed at Stockholm International Water Institute
- Promote and support collective action for sustainable freshwater governance and management
- Arrange seminars, generate knowledge products, provide advice, facilitate roundtables, workshops and multi-stakeholder groups, etc.

**Register for SWH's newsletter with this QR-code**

# Multi-stakeholder group on Groundwater

- Launched on World Water Day 2022
- Enhance collective learning and investigate solutions in groundwater governance and management
- Focus: Self-sufficiency, sustainability and resilience
- Participants: Public and private sector, academia, and interest groups
- Open seminars, policy brief, etc.

PROJECT: SWEDISH WATER HOUSE

## Groundwater

The groundwater multi-stakeholder group focuses on how to make the invisible more visible, which is crucial for sustainable water provision and for resilient ecosystems in facing climate change adaptation and mitigation.

In March 2022, on World Water Day, Swedish Water House established a multi-stakeholder group on Groundwater, aimed at fostering dialogue and sharing of knowledge among actors from various sectors of society. Swedish Water House, under Stockholm International Water Institute (SIWI), has facilitated approximately 20 such collaborations since 2003, many of which have served as an incubator for larger, international initiatives.

# Speakers

**Torleif Dahlin**, Professor at LTH/Lund University Faculty of Engineering

**Frederikke Storm Hansen**, Project Coordinator at the Danish Ministry of Environment

**Esben Auken**, Adjunct Professor at Aarhus Geoinstruments /Aarhus University

**Peter Dahlqvist**, Senior Geologist at SGU (Geological Survey of Sweden)

**Tina Martin**, Researcher at LTH/Lund University Faculty of Engineering

# The Invisible Water

-

## why we need better knowledge  about the groundwater

Torleif Dahlin, Professor

Engineering Geology, LTH/Lund University

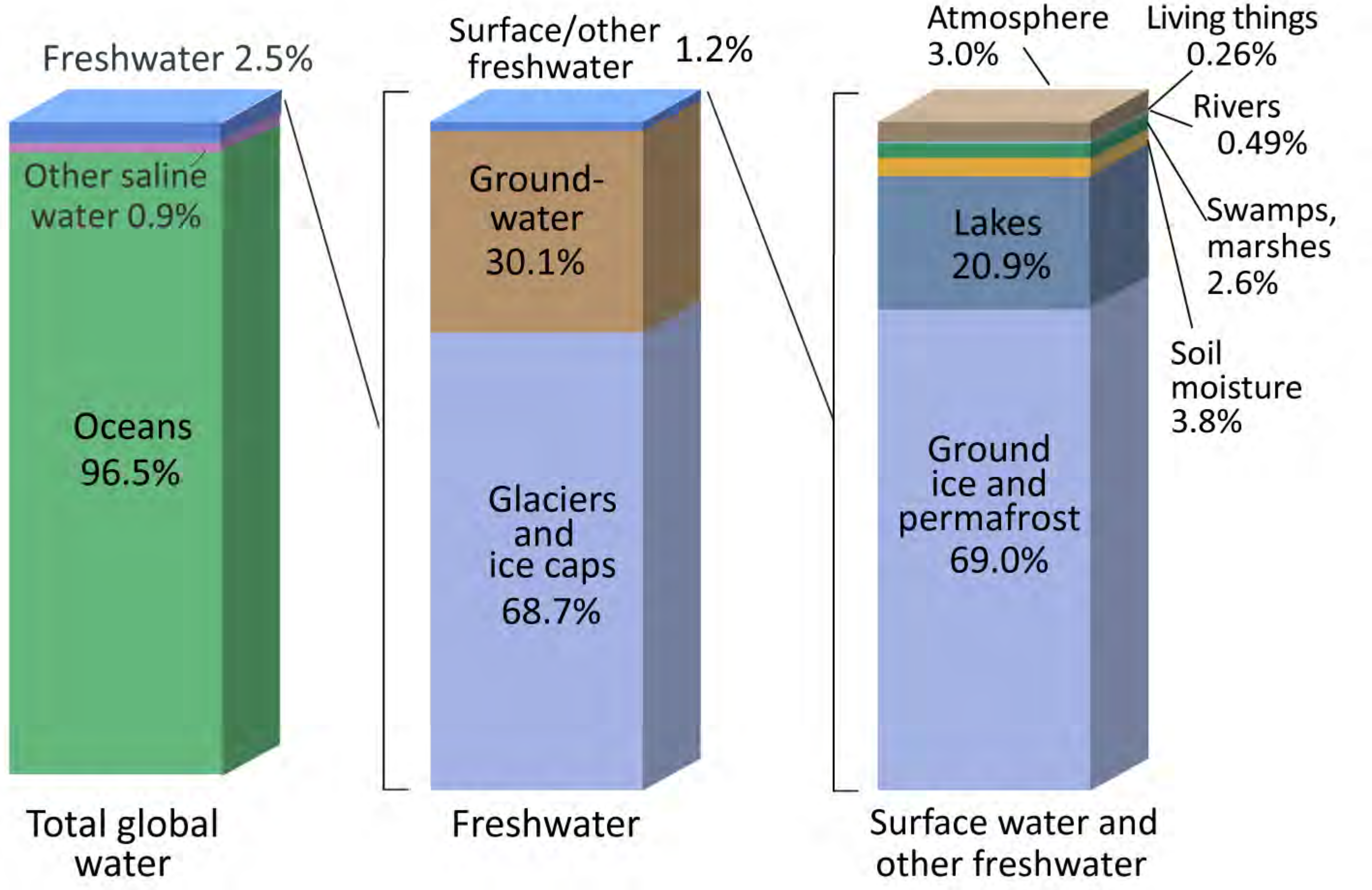
Umzingwani River, Zimbabwe: Example of sand river with surface water a short part of the year and where groundwater is found at about 1 metres depth

# Groundwater

- What is groundwater?
- Is it important?
- Where is it?
- How about recharge of groundwater?
- How about groundwater quality?
- How about groundwater in other parts of the World?
- Do we need  to bother about other parts of the World?
- What needs to be done?

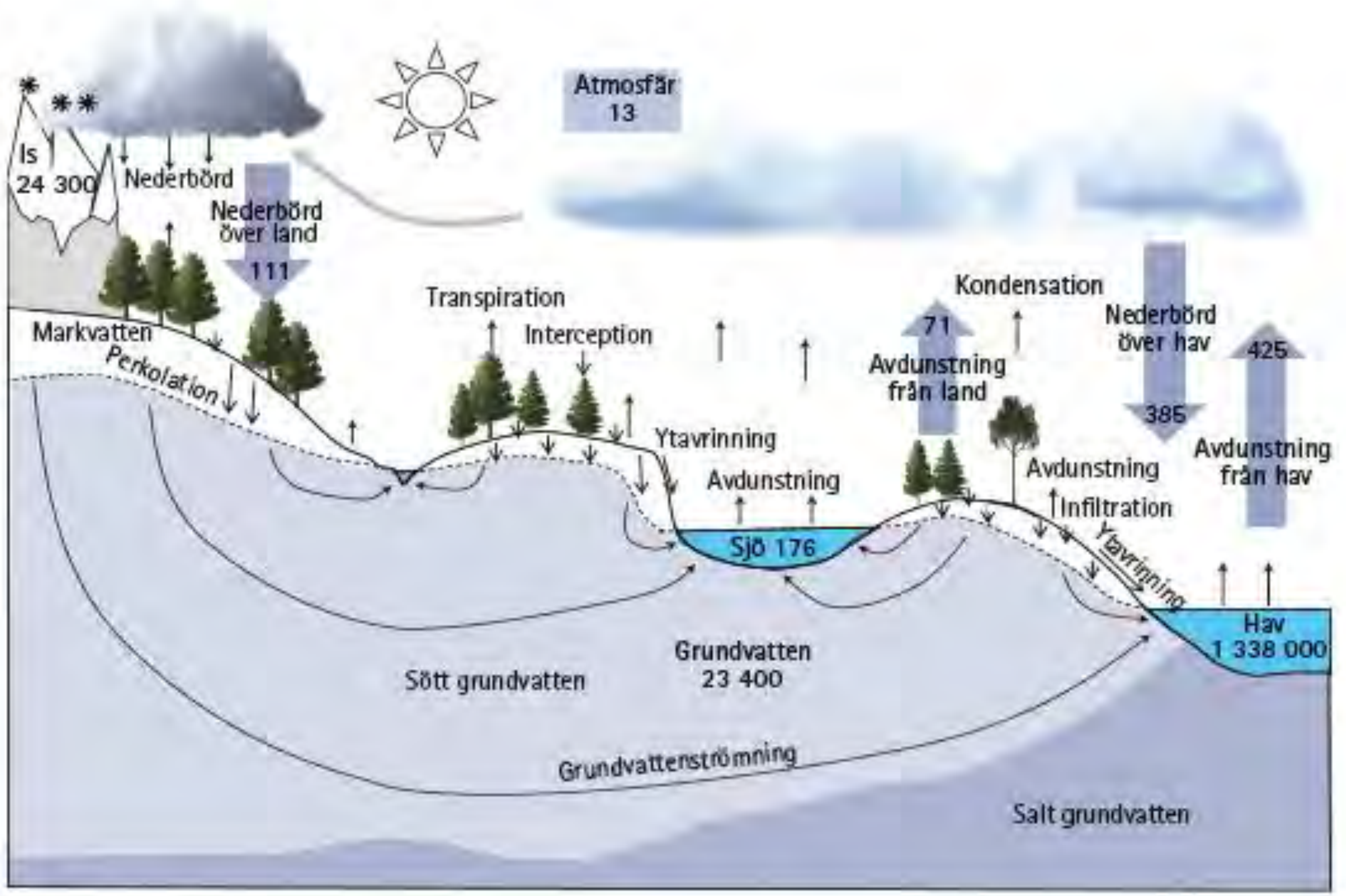
# Key facts about groundwater

- 99 % of all fresh water in fluid form is groundwater
- Most of the surface water comes from groundwater
- The groundwater is depleted or contaminated in many areas




https://www.usgs.gov/media/images/distribution-water-and-above-earth

# The water circulation

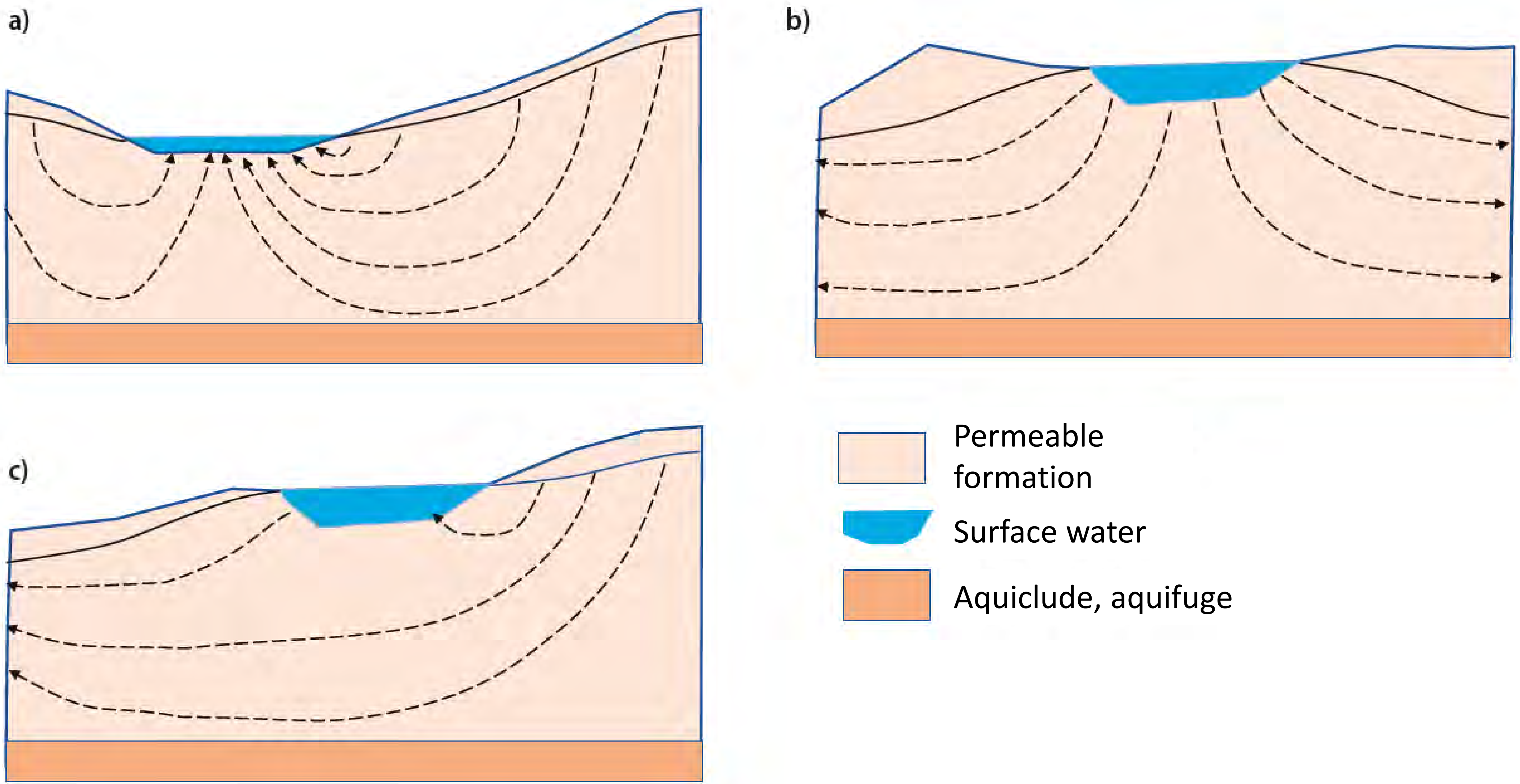



Source: "Grundvattenboken" 2022 Sparrenbom & Jeppsson (red.)

Specified values refer to:

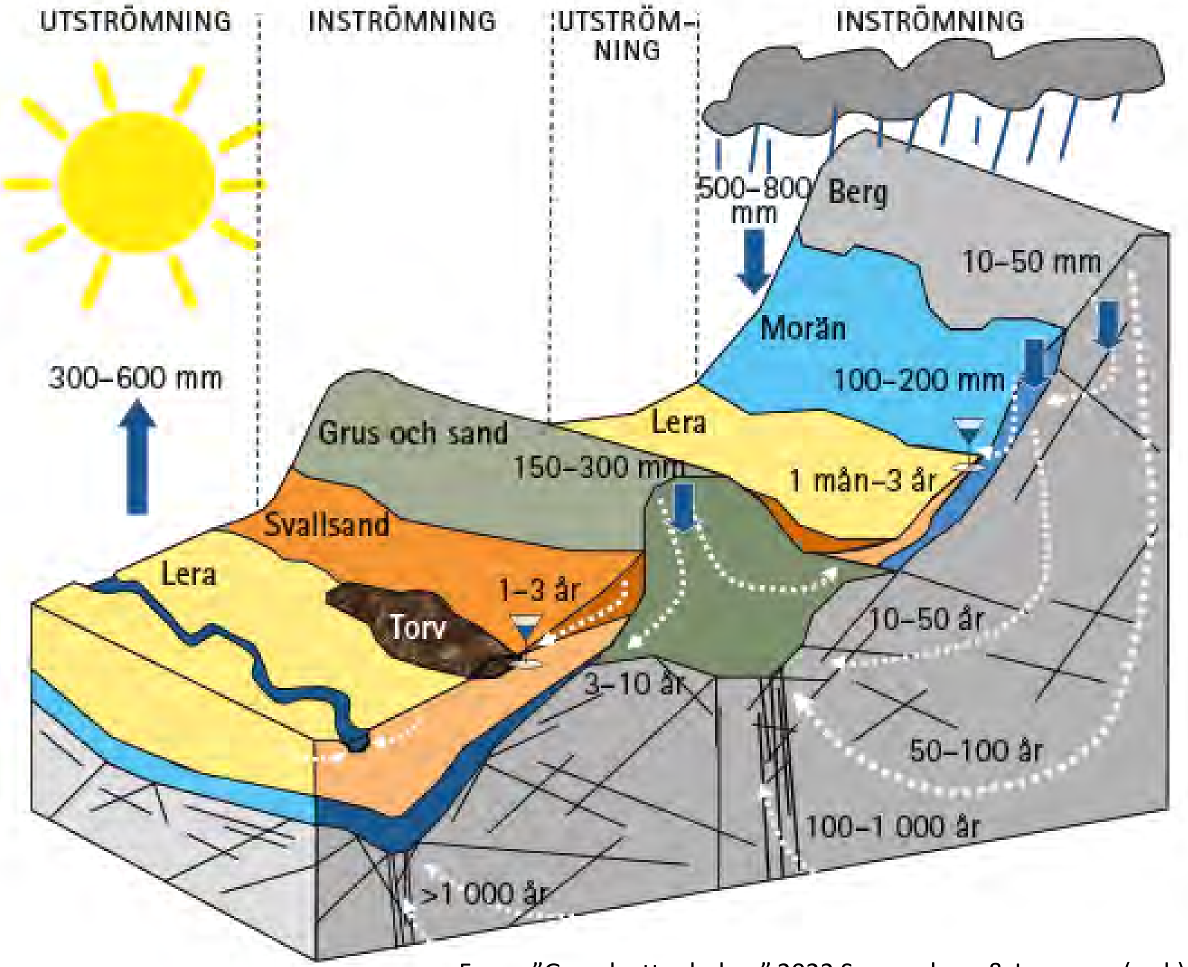
- Thousands km$^3$ (reservoirs)
- Thousands km$^3$/year (flow)

# Exchange between surface water and groundwater




Source: ”Grundvattenboken” 2022 Sparrenbom & Jeppsson (red.)

# Principle groundwater flow in typical Swedish terrain




From: ”Grundvattenboken” 2022 Sparrenbom & Jeppsson (red.)



Traditionally Sweden is believed to have abundant water resources of good quality – is this true?

# Water supply in Sweden

Approx. 50 % surface water and 50 % groundwater (about ½ managed aquifer recharge)

- Surface water requires more advanced cleaning
- Key concerns:
  - Cryptosporidium and other parasites, algea bloom, bacteria
  - Chemical contamination
  - Browning of water

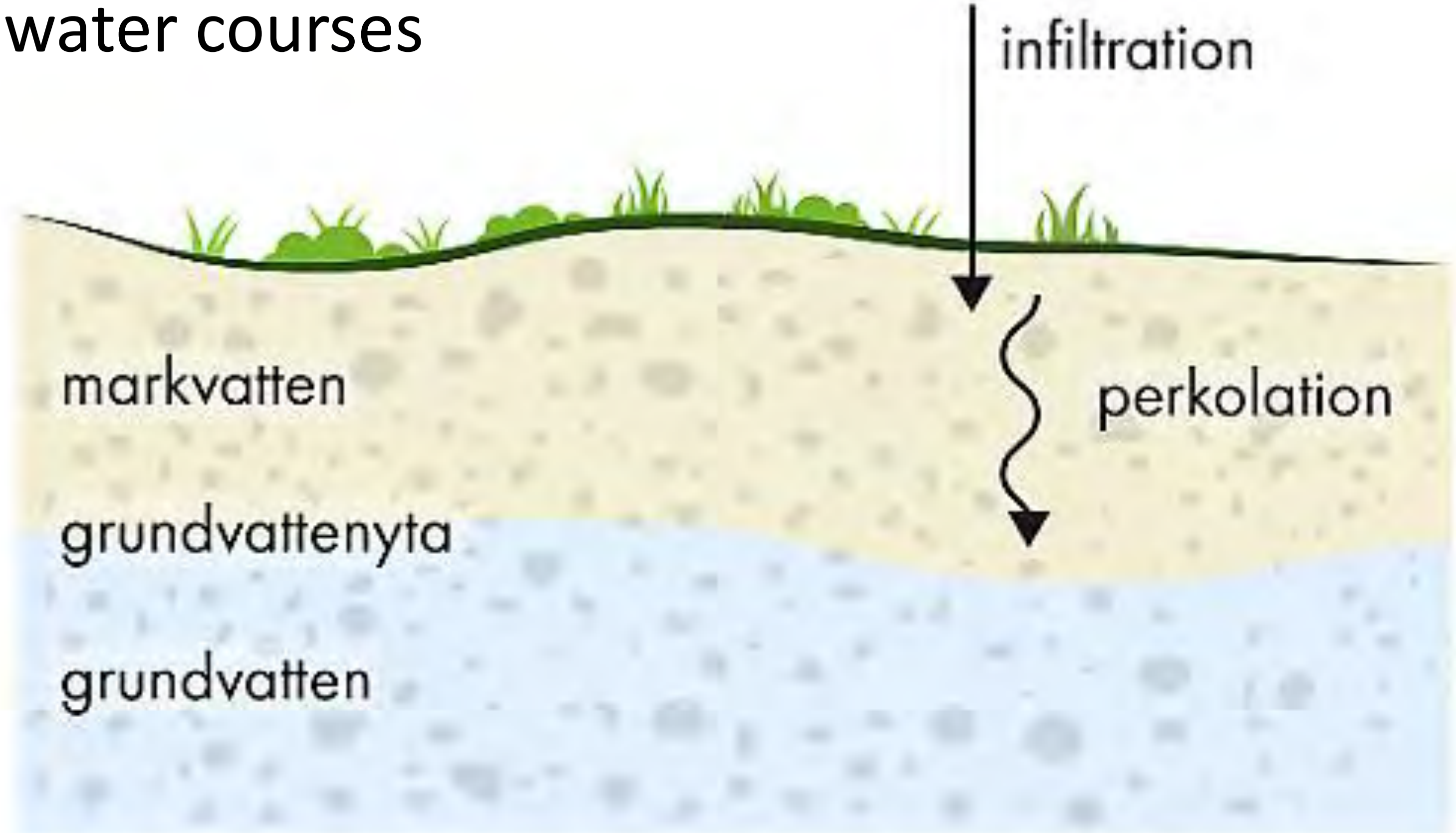
- Groundwater cleaning generally simpler, in some cases no cleaning needed
- Key concerns:
  - Climate change
  - Environmental change
  - Increased demand
  - Contamination from nitrate, pesticides, PFAS, road salt, etc.

- Other threats?
  - Terrorist actions
  - Armed conflicts

https://www.svensktvatten.se/vattentjanster/dricksvatten/vattenverk-och-reningsprocesser/reningsprocesser-i-vattenverk/

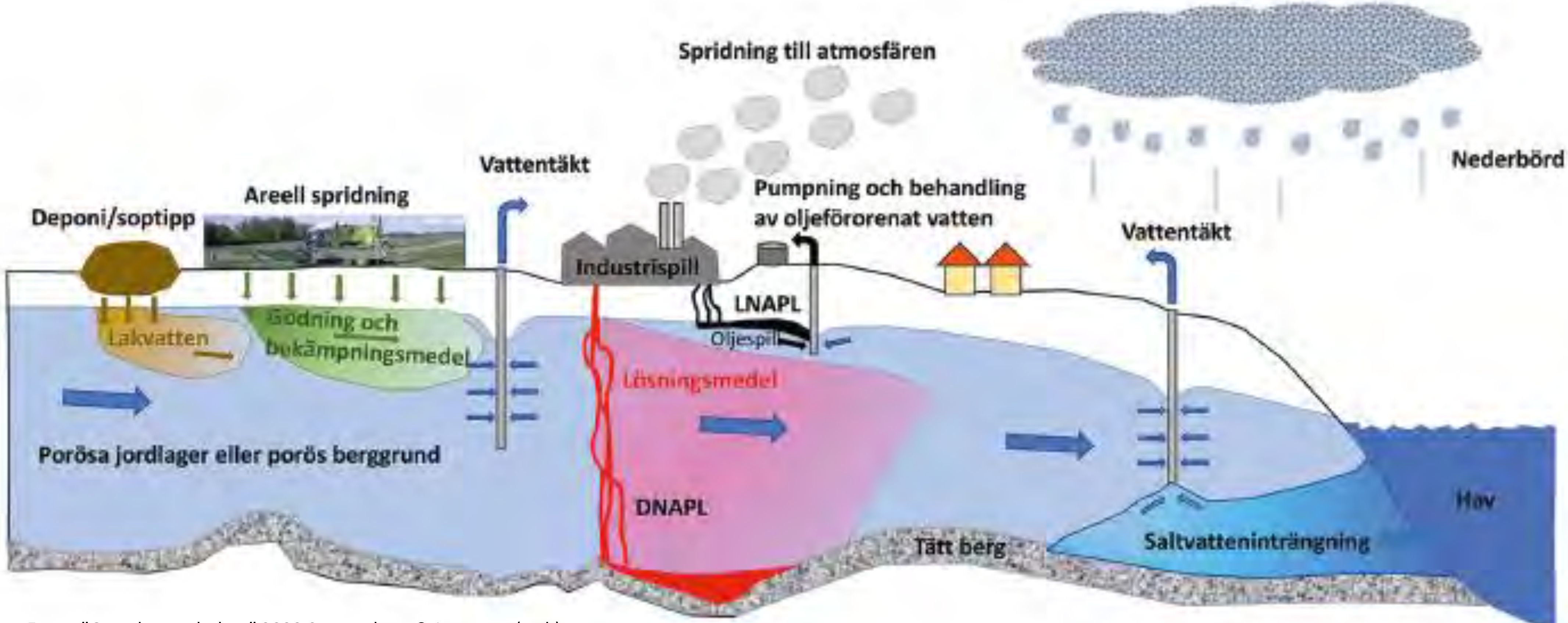
# Factors that affect groundwater recharge

- Climate change (change in precipitation, evaporation, etc.)
- Paved surfaces (roads, parking spaces, buildings, etc.)
- Ditching and drainage
- Straigtened and channeled  water courses
- Reduced wetlands




https://www.smhi.se/kunskapsbanken/hydrologi/mark-och-grundvatten

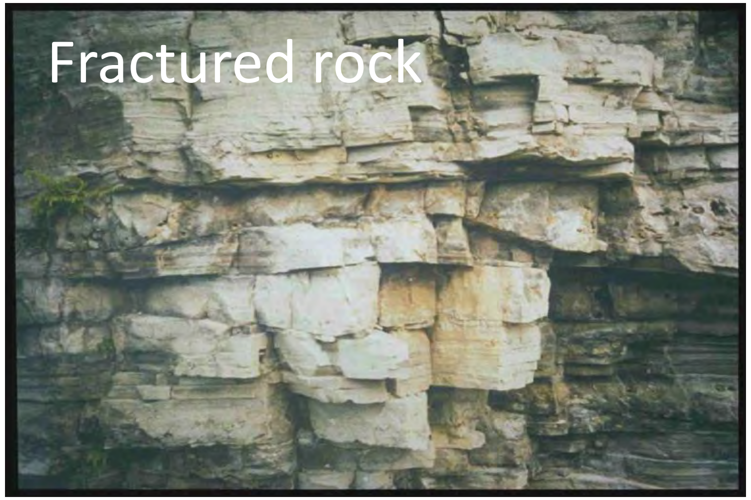
# Threats against the groundwater quality




From: ”Grundvattenboken” 2022 Sparrenbom & Jeppsson (red.)

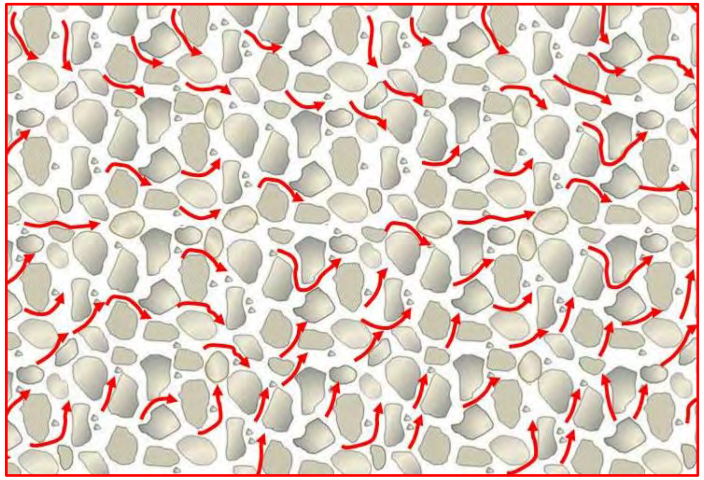
Lowering of the groundwater level leads to oxidation and dissolution of naturally occuring substances in the ground, e.g. sulphur, arsenic, etc.

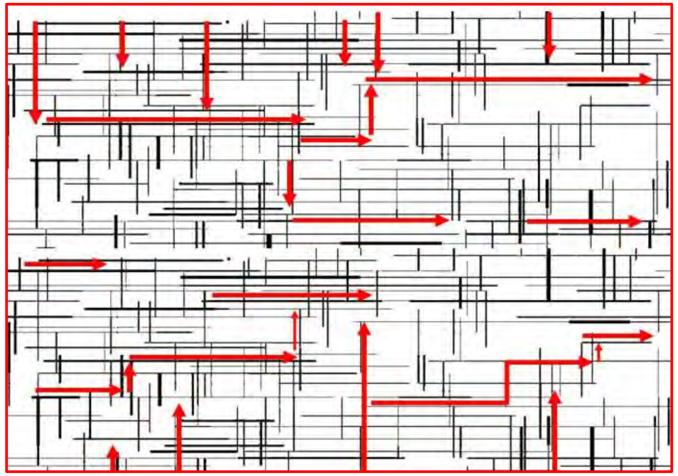
# Groundwater moves slowly but fast enough so that contaminants can spread over large areas during decades


0.1-1 m/day

1-10 m/day



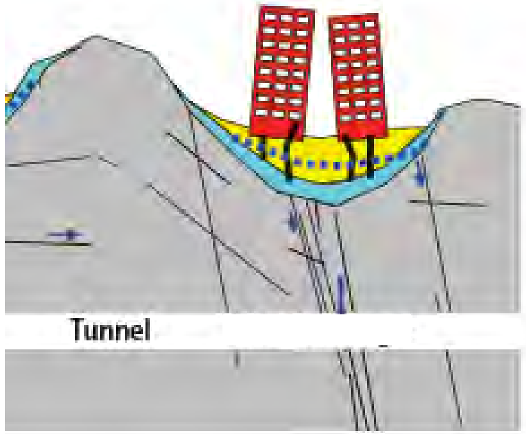


Source: John Cherry

# Groundwater vs. infrastructure and urban areas

In construction projects groundwater is a key concern, because:

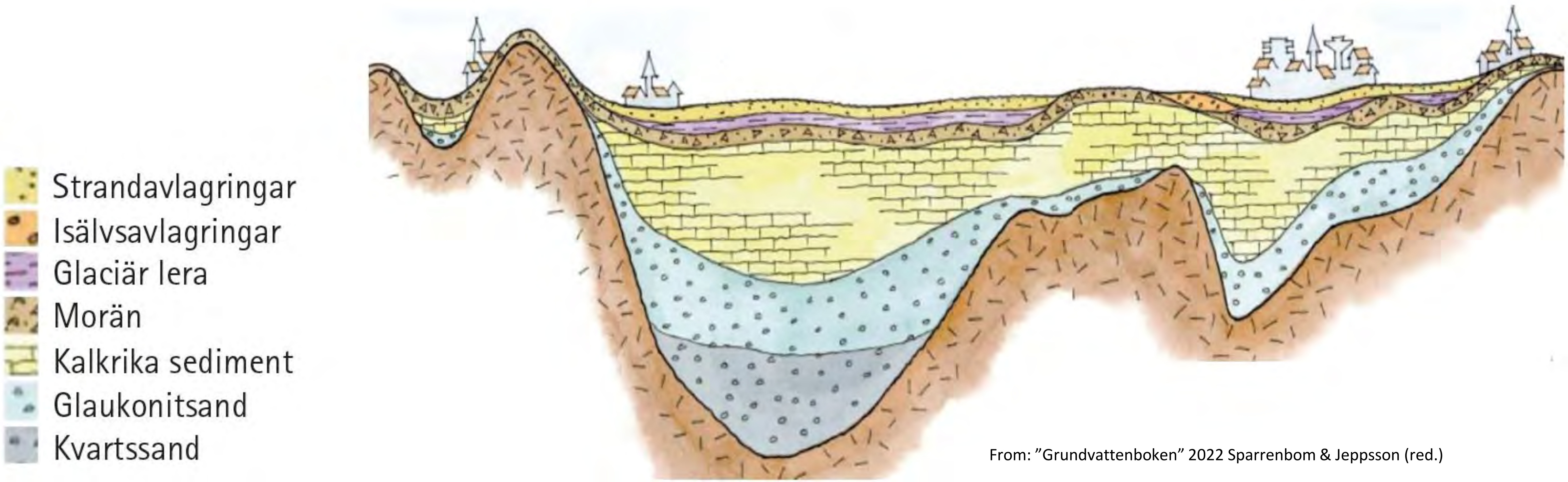
- Inflow can affect stability
- Lowering can cause subsidence in buildings and other infrastructure
- Lowering can negatively affect groundwater sources and ecosystems
- Increased gradients can lead to transport of pollutants from contaminated areas
- Lowering can lead to oxidation of pollutants and naturally occurring substances that can later be transported with the groundwater.




From "Grundvattenboken" 2022 Sparrenbom & Jeppsson (red.)

Good knowledge about groundwater is a key factor for sustainable construction!

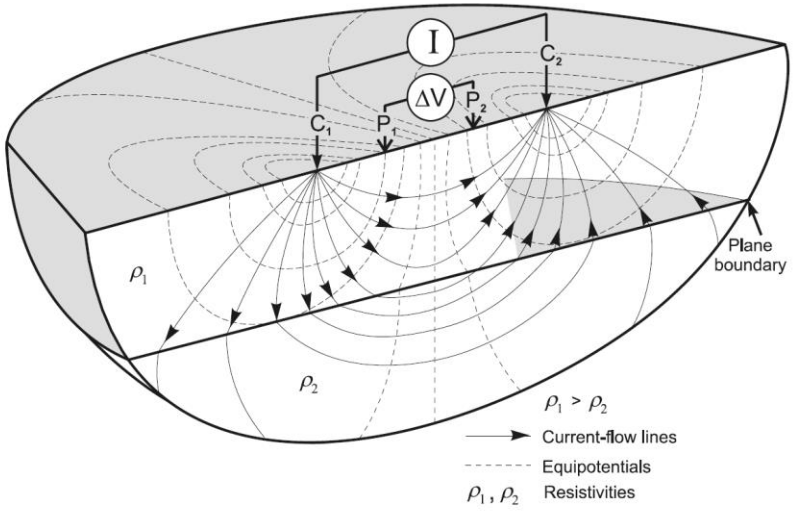
# Kristianstad plain – Sweden’s largest groundwater resource




From: ”Grundvattenboken” 2022 Sparrenbom & Jeppsson (red.)

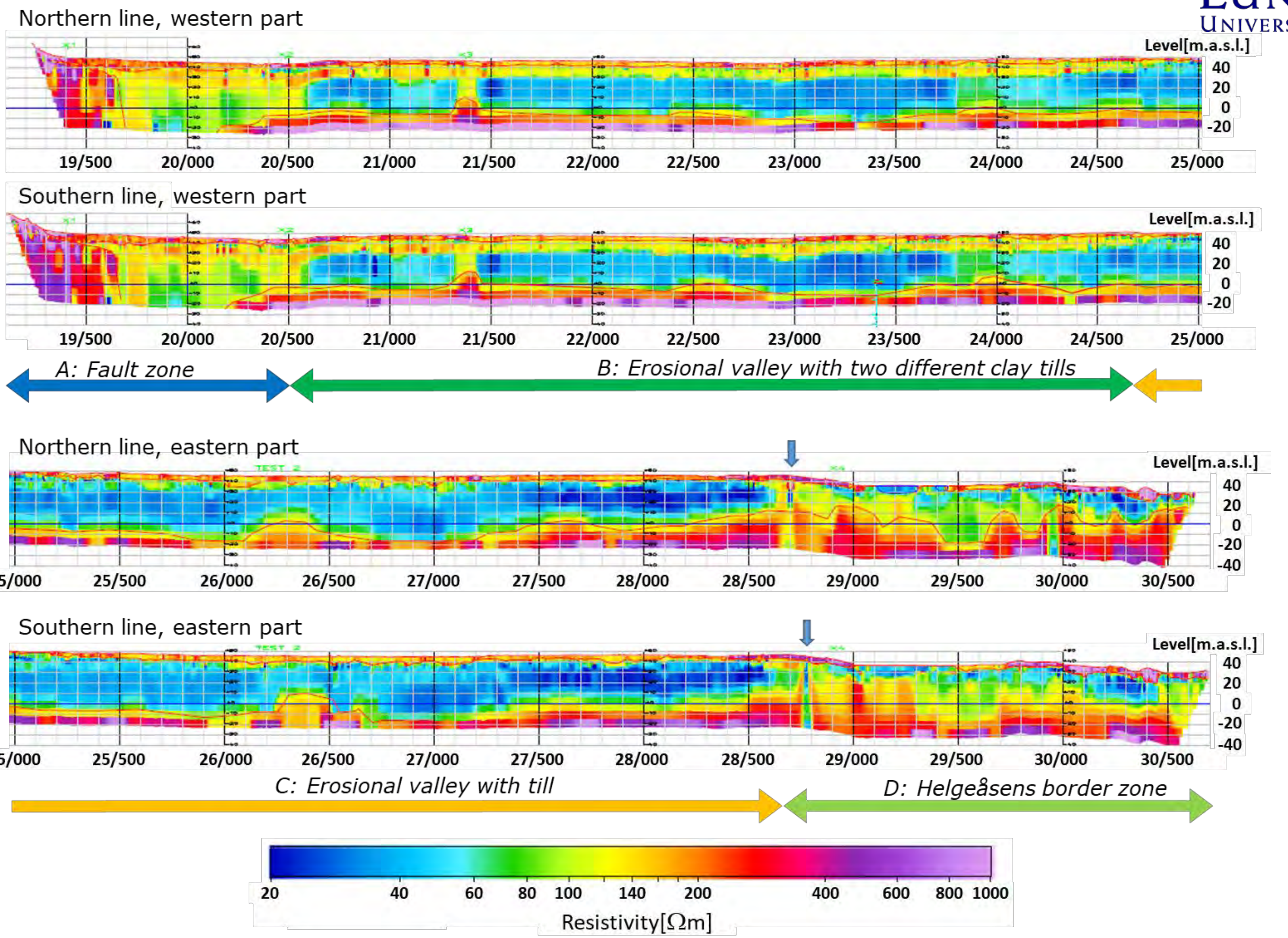
How protect from risk for contamination from new motorway?

# ERT (electrical resistivity tomography) for vulnerability assessment



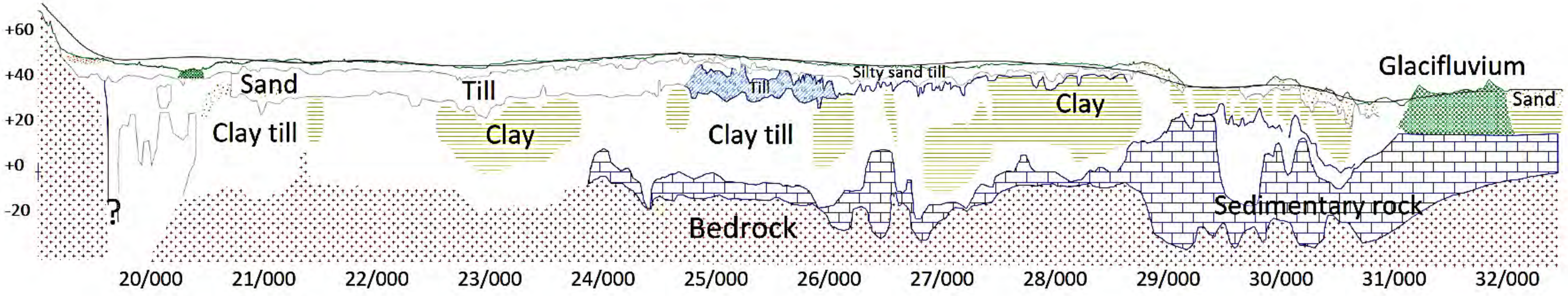

From: Knödel, K., Lange, G. & Voigt, H.J., (2007) *Environmental Geology – Handbook of Field Methods and Case Studies*. Springer, p 205 – 238.

Photo: Tina Martin




From: Dahlin T., Hammarlund E. and Wisén R. (2023) Chapter 50 Case: groundwater vulnerability assessment for new motorway using ERT, in *Engineering Geophysics*, ed. Bondo Medhus A. and Klinkby L., CRC Press, p 299-302

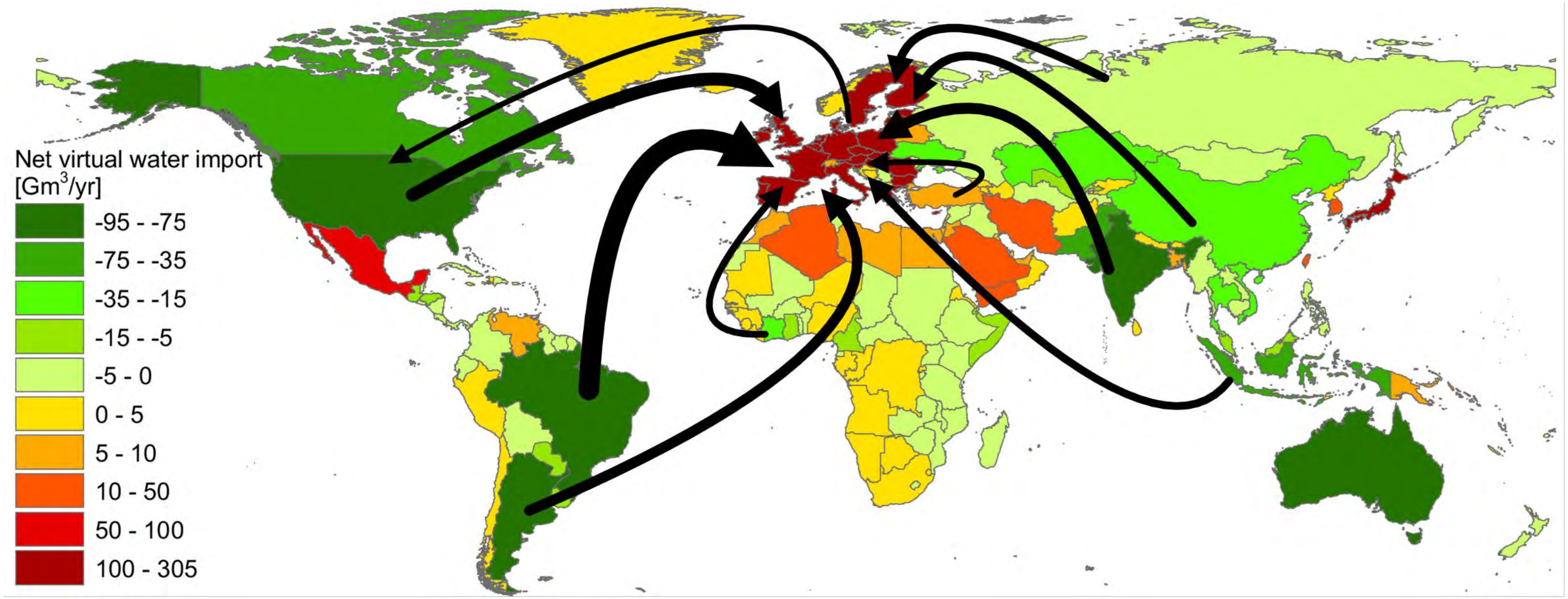
# Interpreted geological section based on ERT and drilling




Thanks to continuous (hydro)geological information impervious ditches were only required in limited parts. This led to savings around 50 million SEK (5 million EUR).

From: Dahlin T., Hammarlund E. and Wisén R. (2023) Chapter 50 Case: groundwater vulnerability assessment for new motorway using ERT, in *Engineering Geophysics*, ed. Bondo Medhus A. and Klinkby L., ISBN 9781032026886, CRC Press, p 299-302

# Globalisation drives virtual water flow and unsustainable groundwater use




https://waterfootprint.org/en/water-footprint/national-water-footprint/virtual-water-trade/

## 40 % of Europe's water consumption is located in other parts of the World

Based on: Hoekstra, A.Y., Mekonnen, M.M. (2012) The water footprint of humanity, Proceedings of the National Academy of Sciences, 109(9): 3232-3237.

# Water is invested in agricultural products: virtual water

- 1 kg cabbage 200 litres
- 1 kg potatoes 250 litres
- 1 kg maize 900 litres
- 1 kg bread (of wheat flour) 1 300 litres
- 1 kg rice 3 400 litres

- 1 litre milk 1 000 litres
- 1 kg cheese 5 000 litres
- 1 kg chicken 3 900 litres
- 1 kg pork meat 4 800 litres
- 1 kg beef meat 15 500 litres

- 1 kg cotton 10 000 litres

https://www.waterfootprint.org/resources/Hoekstra-2008-WaterfootprintFood.pdf

# Half of Sweden’s food is imported

LUND UNIVERSITY


Tomatoes from Morrocco

“Export of farm products has led to large economic development and employment, at the expense of unsustainable groundwater depletion”

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

ELSEVIER

Globalization and the sustainable exploitation of scarce groundwater in coastal Peru

Jana Schwarz*, Erik Mathijs

*KU Leuven, Department of Earth and Environmental Sciences, Division of Bioeconomics, Celestijnenlaan 200e, 3001 Leuven, Belgium*

# Groundwater and food production

- 40% of the global agriculture is irrigated
- 70% of irrigation water is groundwater
- This includes 40% from wells and 30% from baseflow in water courses fed by groundwater
- >70 % of the pumped groundwater goes to irrigation

During long periods of draught almost all food comes from groundwater

https://iah.org/wp-content/uploads/2015/11/IAH-Food-Security-Groundwater-Nov-2015.pdf

# “Green revolution” in agriculture a dirty revolution for groundwater

- Nitrate, pesticides, etc.
- Excessive groundwater withdrawal

Source: https://api.time.com/wp-content/uploads/2015/02/pesticide-plane.jpeg

Journal of Hydrology 596 (2021) 126103

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

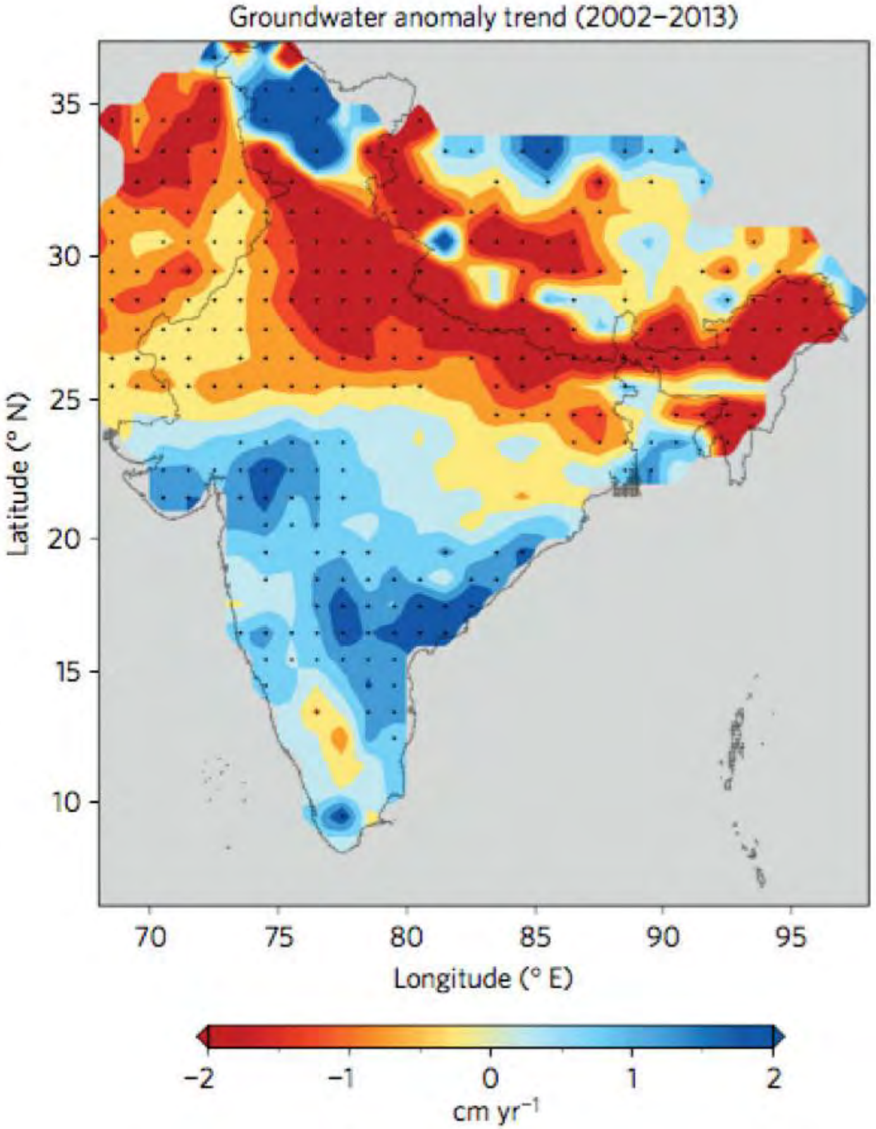
Review papers

Causes and implications of groundwater depletion in India: A review

Swarup Dangar [a], Akarsh Asoka [b], Vimal Mishra [a,b,*]

[a] Civil Engineering, Indian Institute of Technology (IIT) Gandhinagar, Gandhinagar, Gujarat 382355, India
[b] Earth Sciences, Indian Institute of Technology (IIT) Gandhinagar, Gandhinagar, Gujarat 382355, India

Trend in annual groundwater anomaly from GRACE satellite data




Source: World Atlas of Desertification:
https://wad.jrc.ec.europa.eu/groundwaterchanges

# Irrigation leads to salinisation of soils

Source: https://esdac.jrc.ec.europa.eu/content/soil-atlas-europe

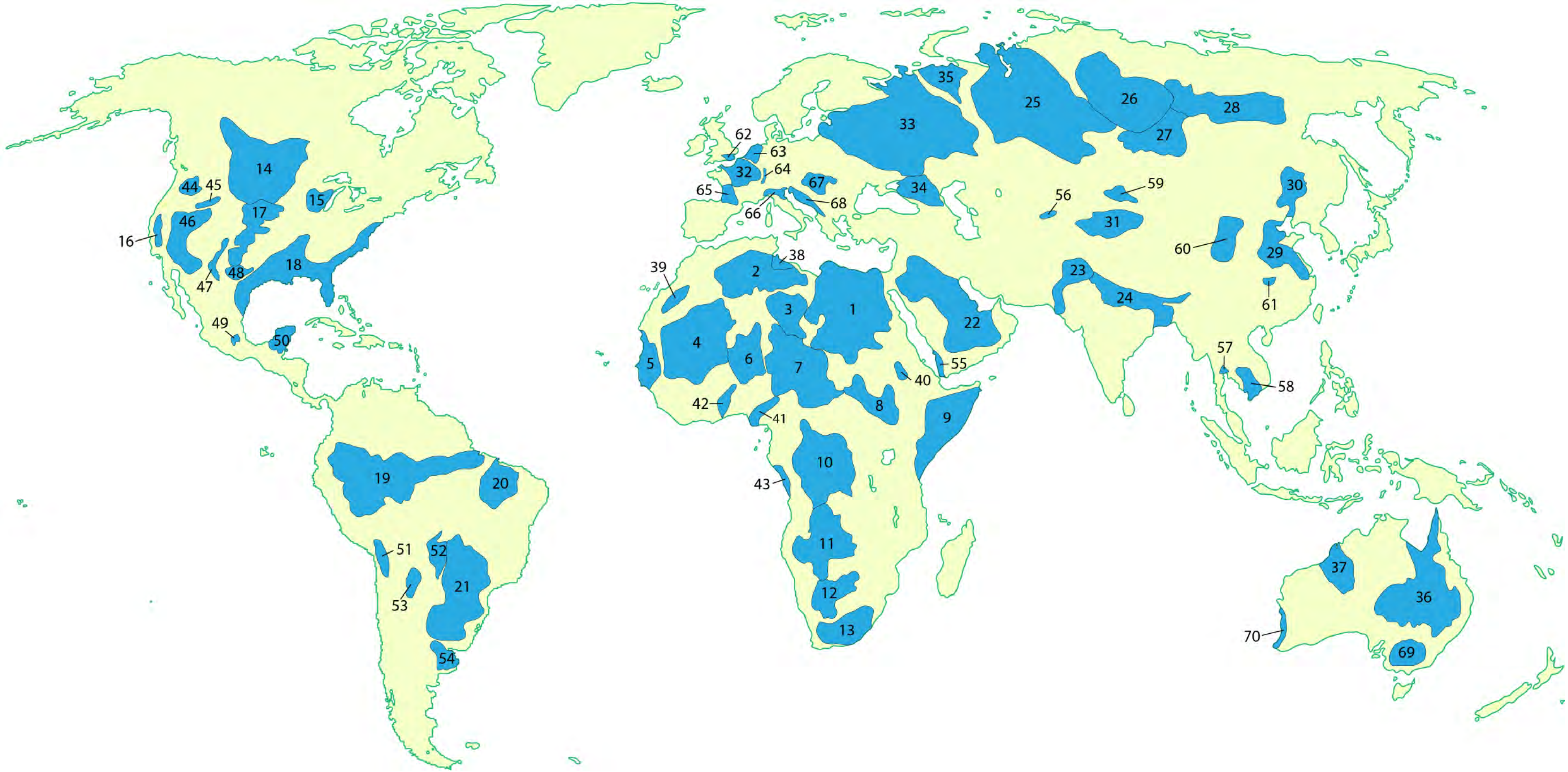
A chronical problem: "gradual salinisation of aquifers from recharge of groundwater from excess irrigation water in many semi-arid areas".

Source: https://potatoes.news/salinization-causes-1166-euros-in-damage-per-hectare-of-potatoes/Daily-News

Foster, S. Pulido-Bosch, A., Vallejos, Á, Molina, L., Llop A., and A.M. MacDonald. 2018. Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions. *Hydrogeology Journal*

# Large akvifers account for 40 % of all extracted groundwater

LUND UNIVERSITY

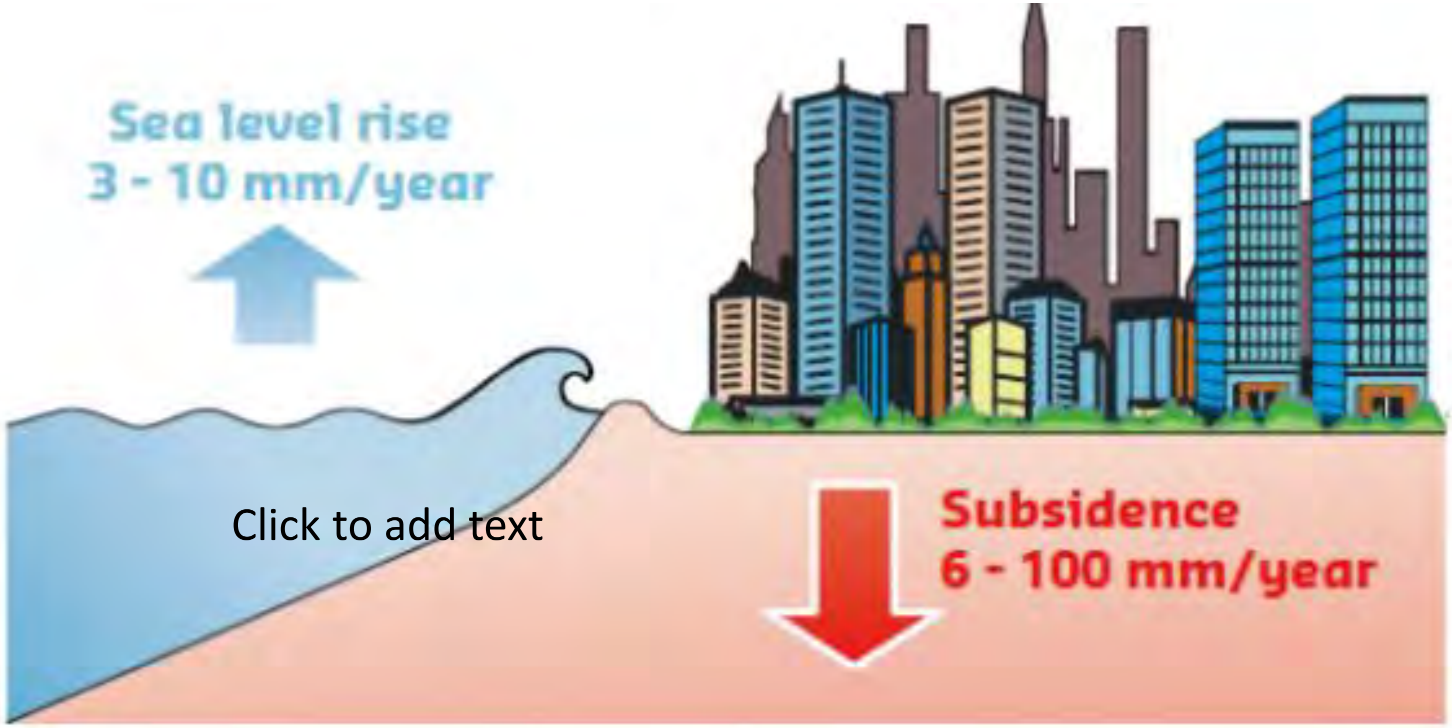



1/3 are depleted beyond recovery within a human perspective

# Groundwater depeltion leads to sea level rise

Groundwater pumping in excess of recharge contributes to 25 % of the mean sea level rise

*Wood and Hyndman 2018*

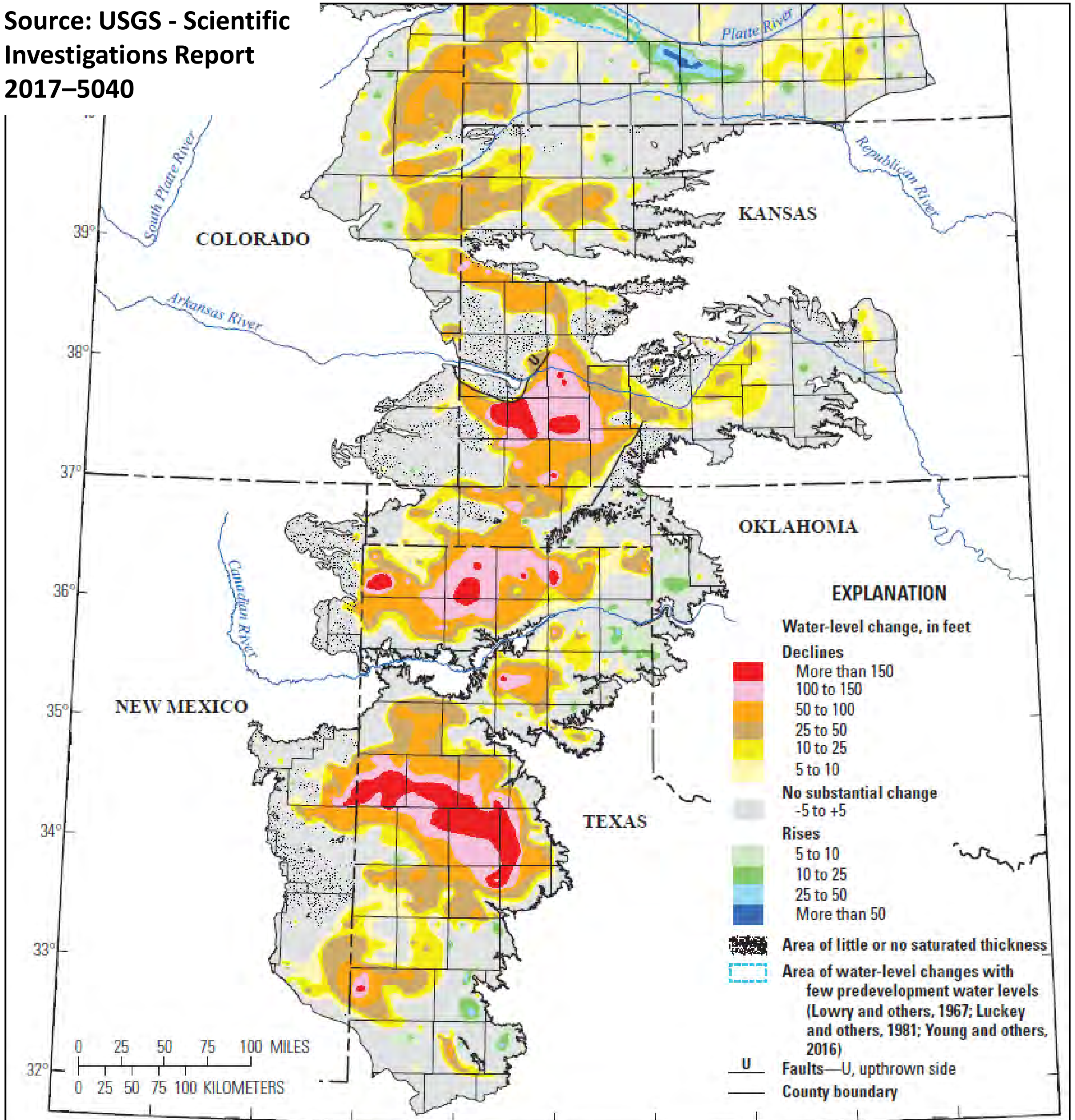



*Erkens, G.; Bucx, T.; Dam, R.; de Lange, G.; Lambert, J. (2015). Sinking coastal cities. Proceedings of the International Association of Hydrological Sciences.*

Groundwater is the largest cause of relative sea level rise in many coastal cities through the combination of land subsidence and groundwater depletion.

# A third of the World's large aquifers are overexploited beyond recovery

Source: USGS - Scientific Investigations Report 2017–5040




## The High Plains or Ogallala Aquifer, USA



Crop circles in Finney County, Kansas, denote irrigated plots using water from the Ogallala Aquifer. Credit: NASA

# Over exploitation of groundwater is visible from the space


EDITORIAL
The drought you can't see

"… massive losses of groundwater from the aquifer underlying California's agriculturally important Central Valley have occurred since the 1980s"

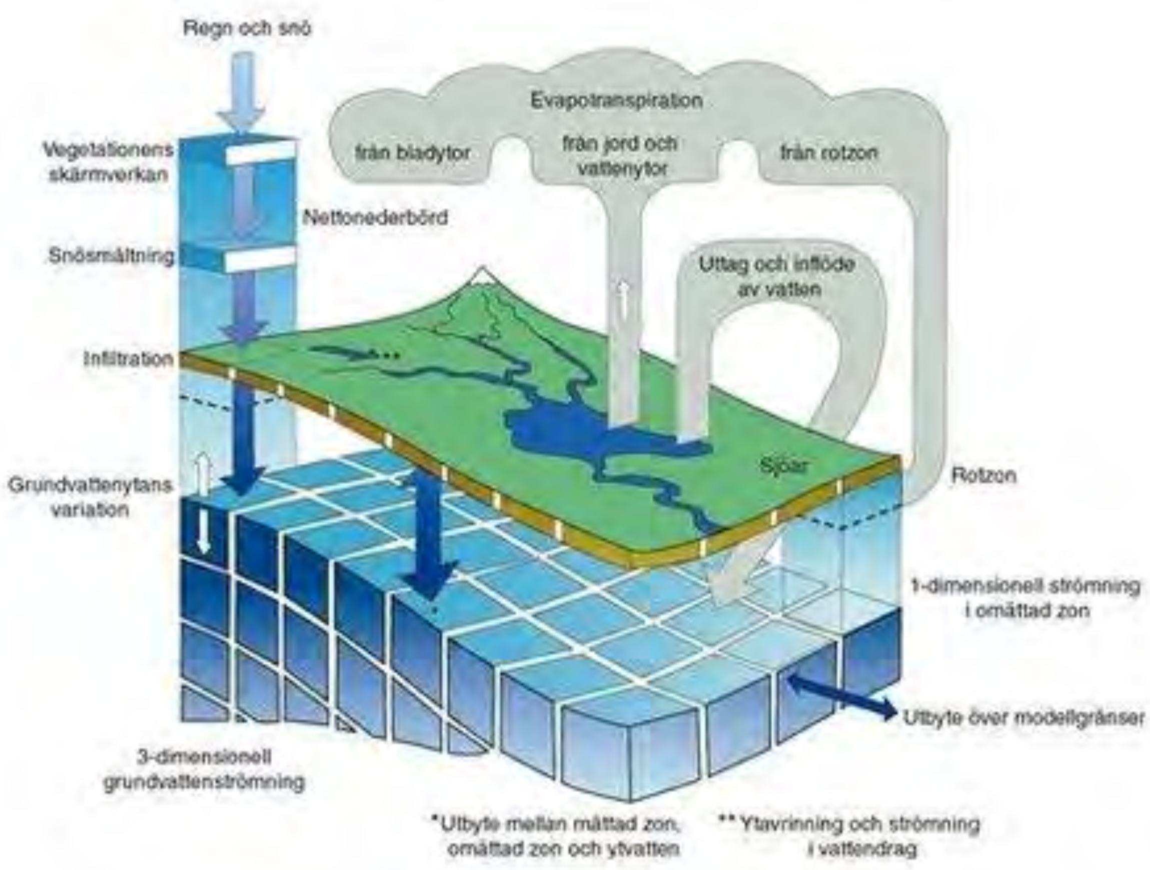
- Global food availability expected to decrease (and prices to rise)
- Increased need to be self-reliant on food
- Demand for productive farming land and irrigation water will increase

(Science, 16 April 2020; https://www.science.org/content/article/droughts-exposed-california-s-thirst-groundwater-now-state-hopes-refill-its-aquifers)

# Motivation for mapping groundwater

- Long term sustainable management needed because of:
  - Climate change
  - Change in recharge
  - Contamination hazards
  - Growing populations
  - Increased need for food production
- Groundwater models (conceptual and numerical) are mostly based on very sparse actual data
- Sustainable construction

Model of Kristianstadsslätten and Listerlandet with tributary areas (total ca 2 350 km$^2$).




Source: https://grundvattenradet.se/grundvattenmodell.html

# Further reading about groundwater

- Swedish groundwater – overview of conditions and current issues: https://siwi.org/publications/groundwater-in-sweden-an-overview-of-the-current-conditions-and-its-potential/
- Online Platform for Groundwater Knowledge: https://gw-project.org/
- UNESCO about groundwater: https://en.unesco.org/themes/water-security/hydrology/groundwater
- European environmental authority: https://www.eea.europa.eu/publications/europes-groundwater
- Water Footprint Network: https://waterfootprint.org/en/
- Grundvattenboken: https://www.studentlitteratur.se/kurslitteratur/teknik-datorer-it-och-bygg/miljoteknik-och-marklara/grundvattenboken
- About groundwater for children (in Swedish, available in many languages): https://gw-project.org/download/valle-och-dianas-grundvattenaventyr-till-den-mattade-zonen/?wpdmdl=9996&refresh=63c4342bae8f71673802795


New textbook on groundwater in Swedish – now being translated to English, expected to be available mid to late spring 2024

# *Grundvattenboken*

CHARLOTTE SPARRENBOM
HANS JEPPSON

Studentlitteratur
VINNANDE VETANDE

# Thanks for your attention!

Karst spring at Goronosa National Park, Mocambique

Thanks to Prof. Emeritus John Cherry and "The Groundwater Project" for inspiration and material for this presentation

Ministry of Environment of Denmark
Environmental Protection Agency

# Groundwater Mapping in Denmark

# Danish Groundwater Statistics

Water supply:
100% drinking water from groundwater
~800 million $m^3$/year

Population: 5.9 million

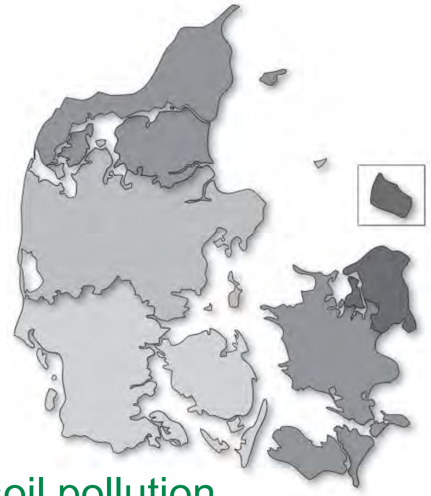
Area: 43 000 km2

Land use:
Agriculture 66 %
Forest 16 %
Lakes, meadows and marsh 7 %
Urban zone/infrastructure 10 %

Water taxes and VAT finances groundwater mapping (among other things like wastewater treatment)

# Danish governmental structure with regards to drinking water

State (Ministry of Environment – Environmental Protection Agency, EPA)
Legislation, Orders, Guides, Approval of pesticides, River basin management plans, Groundwater mapping including vulnerability studies and monitoring



Regional governments (5)
Mapping and monitoring of soil pollution, and cleaning up polluted sites
Permits for extraction of raw materials

Municipalities (98)
Water supply, licenses to extract groundwater and for wastewater treatment, supervision of water utilities, municipal plans, action plans and plans for groundwater protection

# History of Groundwater Management

**1853**

### Cholera outbreak in Copenhagen

4800 people die of cholera due to overpopulation, lack of sanitary installations, and pollution of surface water sources.

**1926**

### Consolidation Act on Water Supply

Groundwater is a common good. License to extract water.

**1974**

### Environmental Protection Act

**1983**

### Contaminated Soil Act

Mapping and remediation of contaminated soil types.

**1986**

### Pesticide Strategy

# History of Groundwater Management

**1987**

### First Aquatic Environment Plan

Regulation on phosphor, wastewater, nitrogen.
Implementation of wastewater treatment in cities to meet new demands.
Mandatory water metering for all consumers.

**1994**

### Non-Revenue Water Penalty Tax

10% Threshold, beyond that utilities must pay a penalty tax

**1998**

### Change – Act on Water Supply

Areas of special drinking water interest.
Groundwater mapping.
Targeted action planning.

**2000**

### EU – Water Frame Directive

Achieve good qualitative and quantitative status of all water bodies.
Improve sustainable water usage.
Enhance protection of water bodies and avoid groundwater pollution.

**2000**

### Zonation

Vulnerability assesement and targeted protection

# History of Groundwater Management

## 2006
### EU - Groundwater Directive
Requires the prevention of hazedous substances to enter the groundwater.

## 2007
### Protection of Near Borehole Areas
Targeted protection near boreholes to secure future drinkingwater resources.

## 2007
### Structual Reform
Responsibility shift from counties to State and municipalities.

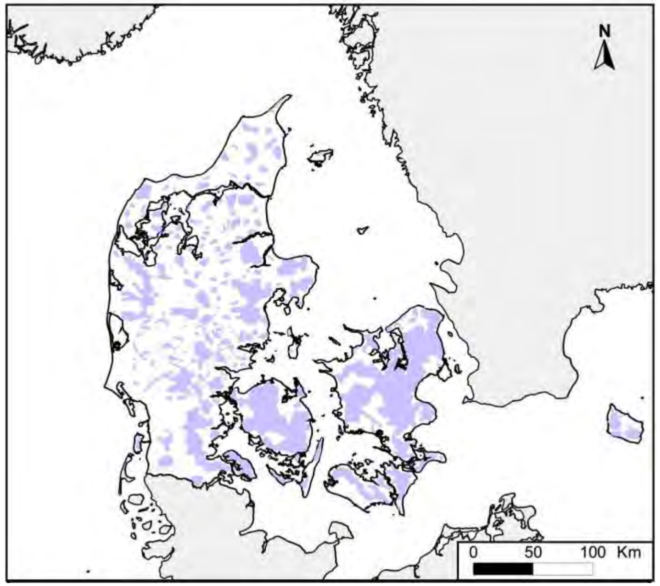
## 2009
### Water Sector Act
Water utilities must be benchmarked to ensure efficiency

## 2015
### Change – Act on Water Supply
**Mapping of groundwater changes to a continuous operational maintenance task.**

# Key Water Policies

- Nitrate & Phosphate regulations
- Pesticide removal
- Well protection zones
- Utilities penalized at above 10% water loss
- Water meters
- Public campaigns
- Water prices – full recovery

Areas of drinking water interest



# Challenges in Denmark

Pesticides from agriculture, industry and private use

Chemical substances from former and present industries

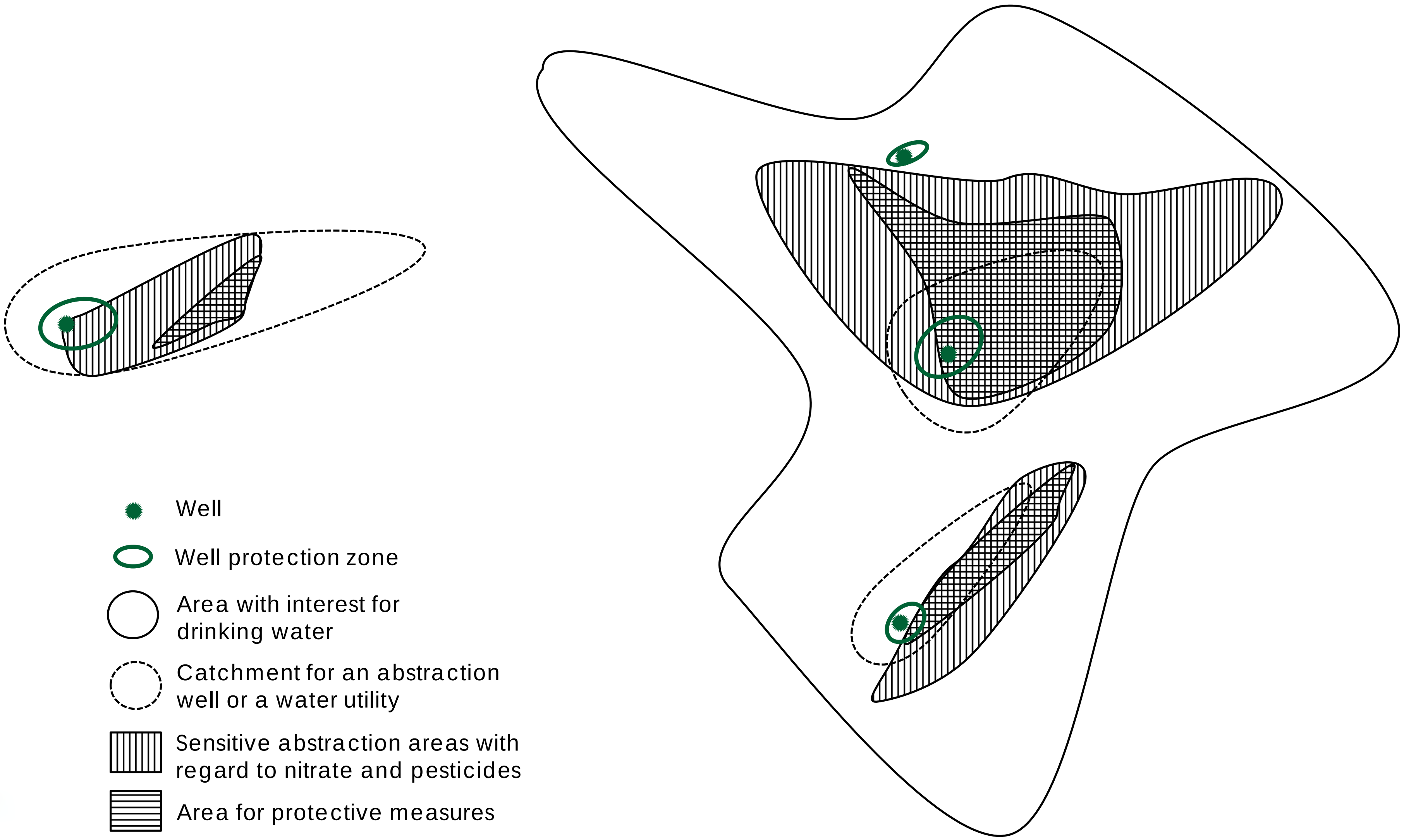
Nitrate from agriculture

Salt water intrusion

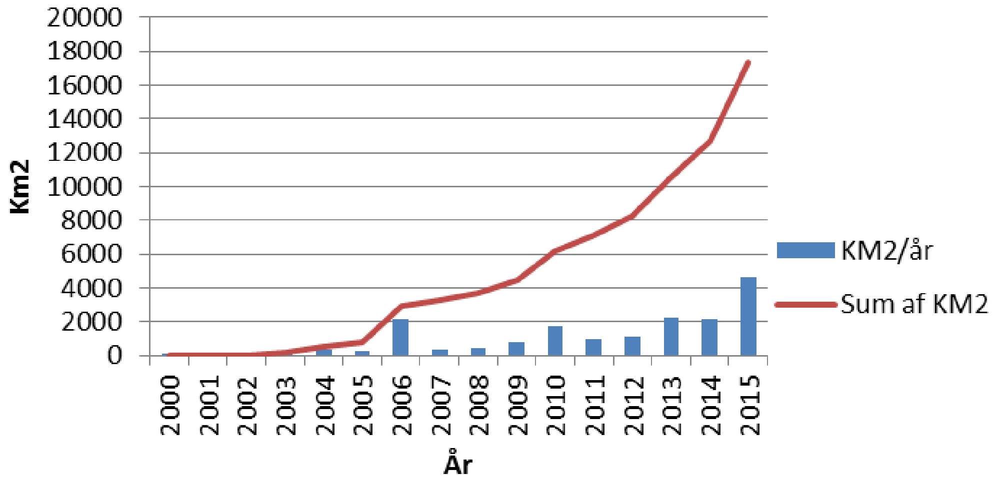
Local problems with different natural occurring substances: Arsenic, fluoride, strontium and others

Overexploitation in major cities

# Targeted Groundwater Protection



# Groundwater Mapping




1999-2015:
Denmark has spent ~360 million Euro mapping 40 % of Denmark

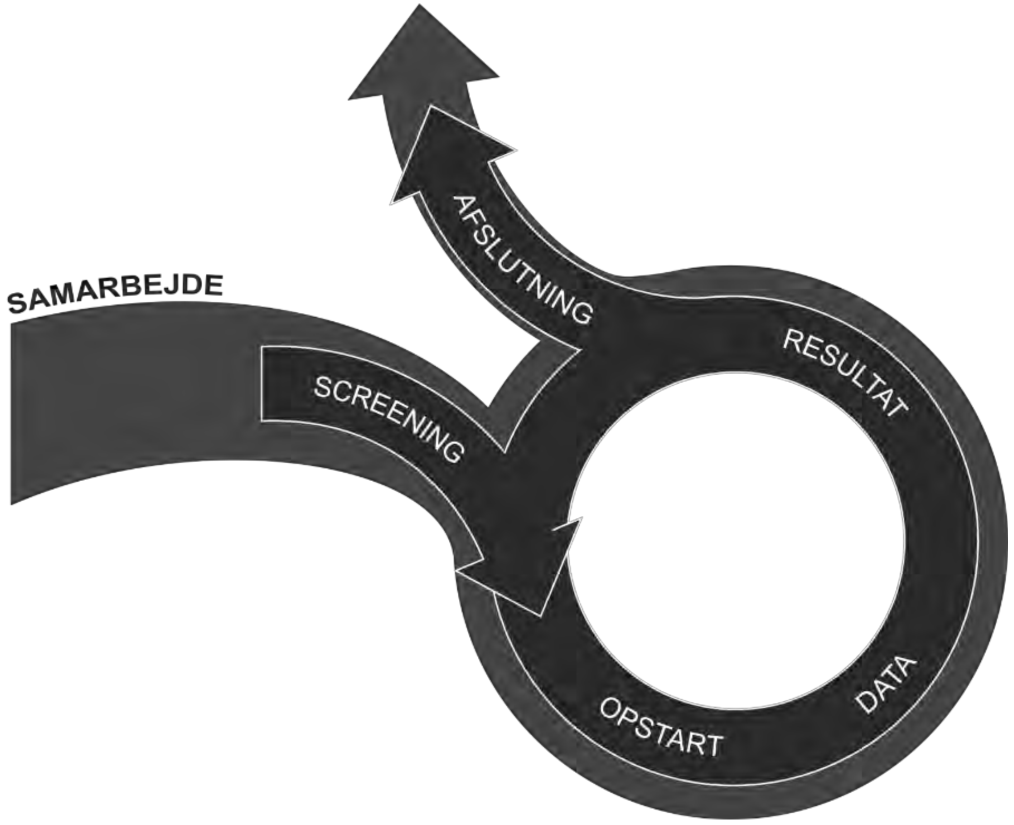
2016-now:
Reduced budget
Continuous updating of existing data and results
National standards and guides for consistency
Methods, databases and software standardised

# Groundwater Mapping Process

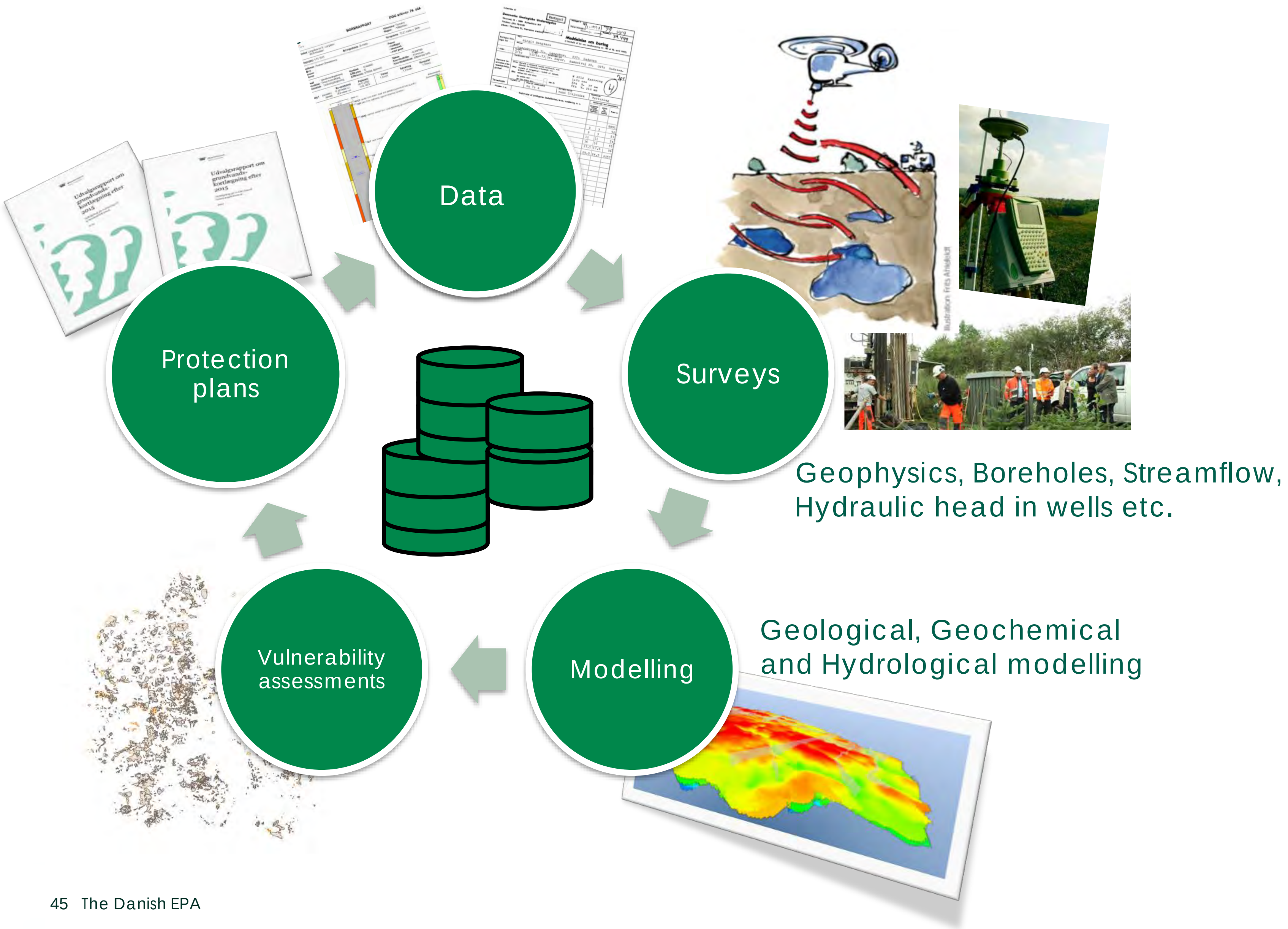
Start-up:
analysis and evaluation of existing literature and data.
Important to keep goal and purpose in mind.
Leading to recommendations for further work and new data.

Data-phase:
collect more data, detailed modelling (geological and hydrological), delineate catchment areas, well protection zones

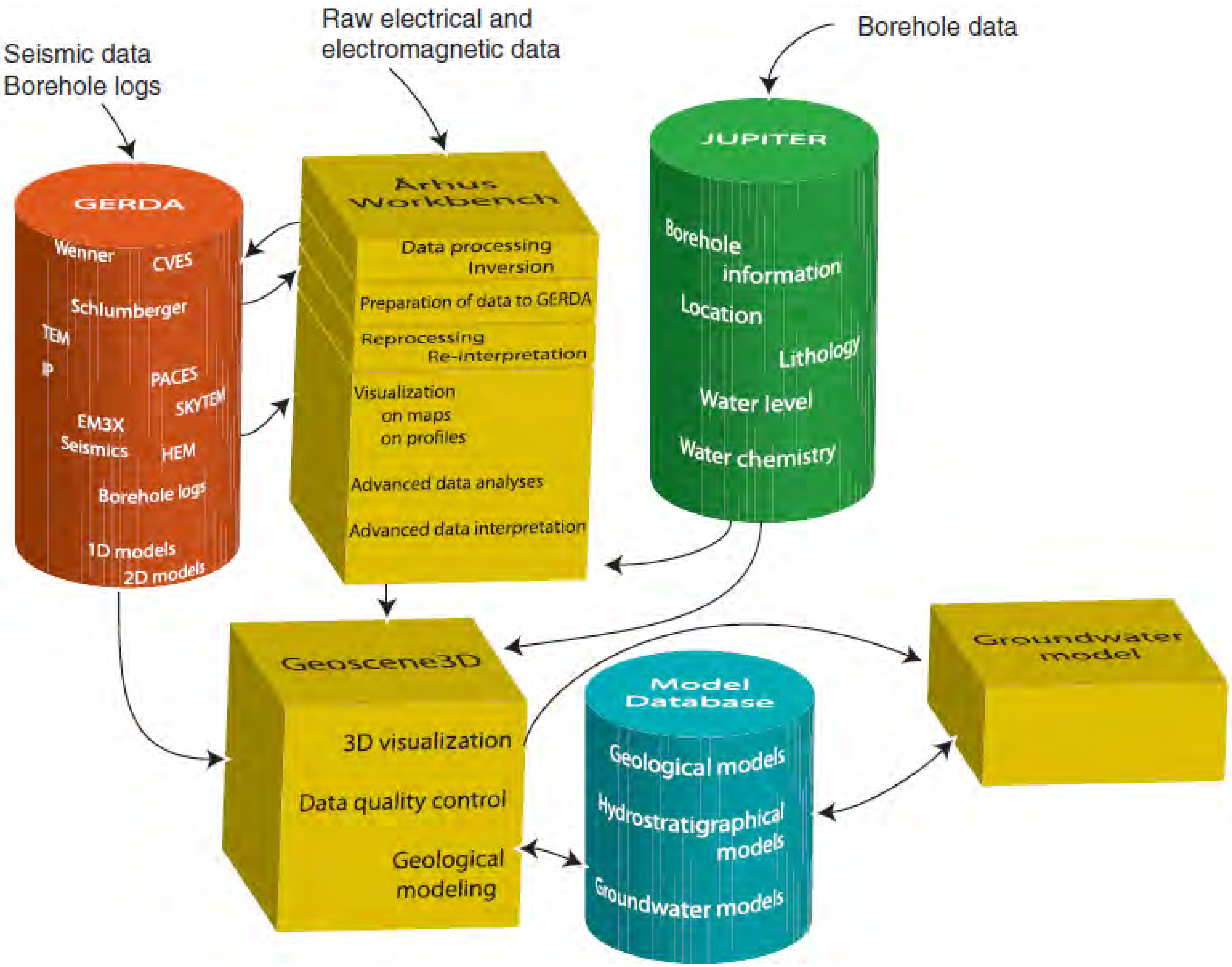
Results:
assessment of vulnerability, areas vulnerable to nitrate, areas for action, designate all themes in order



# Groundwater Mapping Process



# Data



Seismic data
Borehole logs
Raw electrical and
electromagnetic data
Borehole data
GERDA
Wenner
CVES
Schlumberger
TEM
IP
PACES
SKYTEM
EM3X
Seismics
HEM
Borehole logs
1D models
2D models
Arhus Workbench
Data processing
Inversion
Preparation of data to GERDA
Reprocessing
Re-interpretation
Visualization
on maps
on profiles
Advanced data analyses
Advanced data interpretation
JUPITER
Borehole
information
Location
Lithology
Water level
Water chemistry
Geoscene3D
3D visualization
Data quality control
Geological
modeling
Model
Database
Geological models
Hydrostratigraphical
models
Groundwater models
Groundwater
model

# Data – Jupiter

Unique borehole identification numbers (DGU numbers)

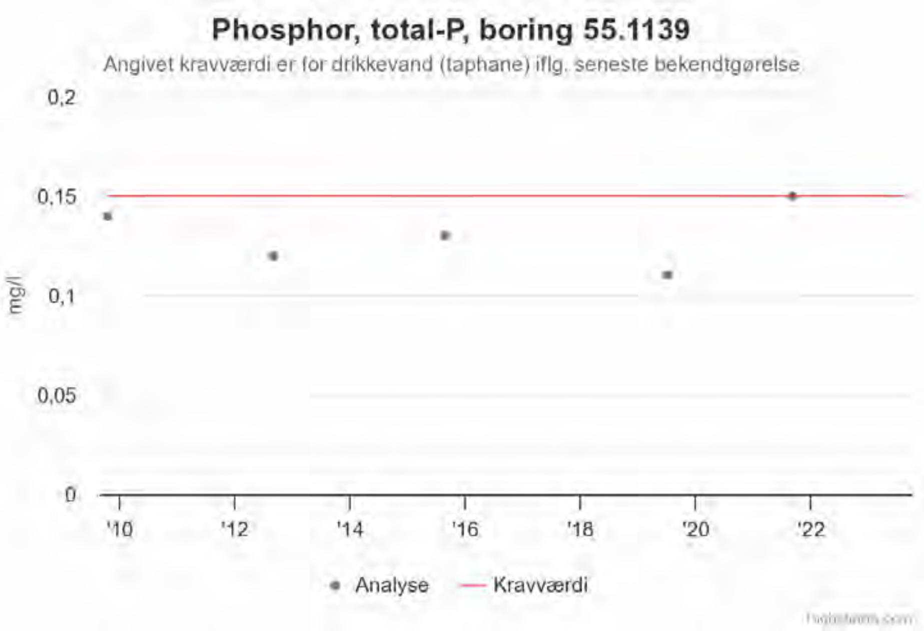
GPS coordinates and measurement method

Lithology records and filter location(s)

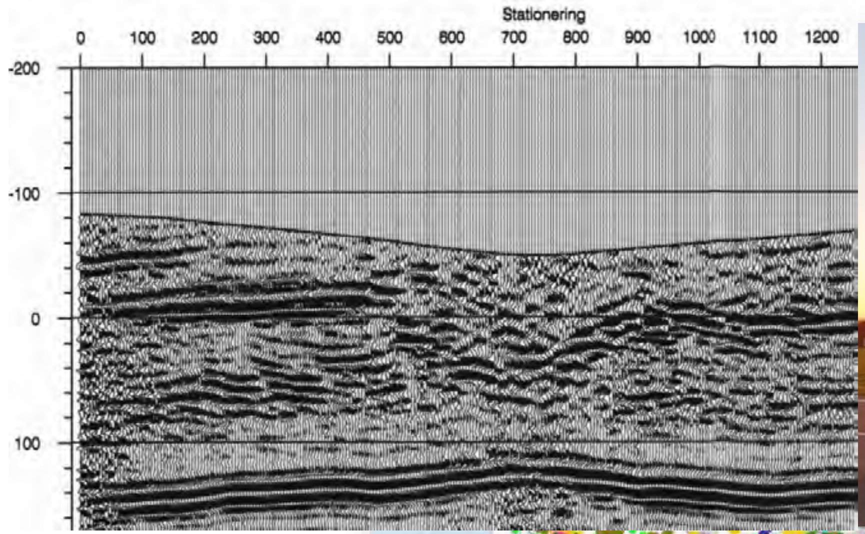
Water level records

Past and current abstraction licenses and records

Water chemistry records

# Data – Gerda


Stationering
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
-200
-100
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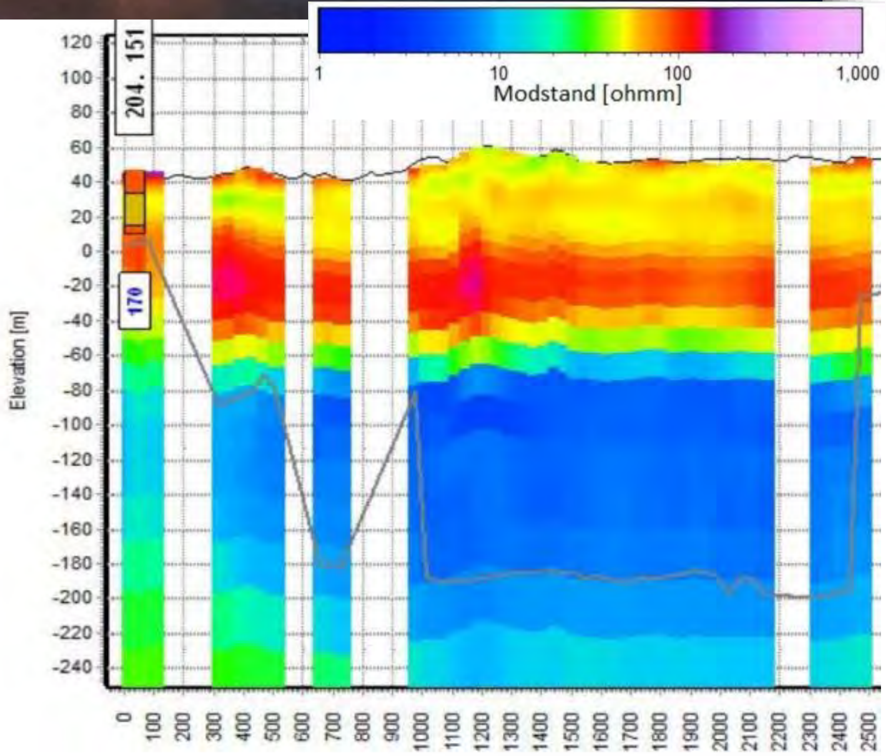
100


Seismics


SkyTEM


1 10 100 1,000
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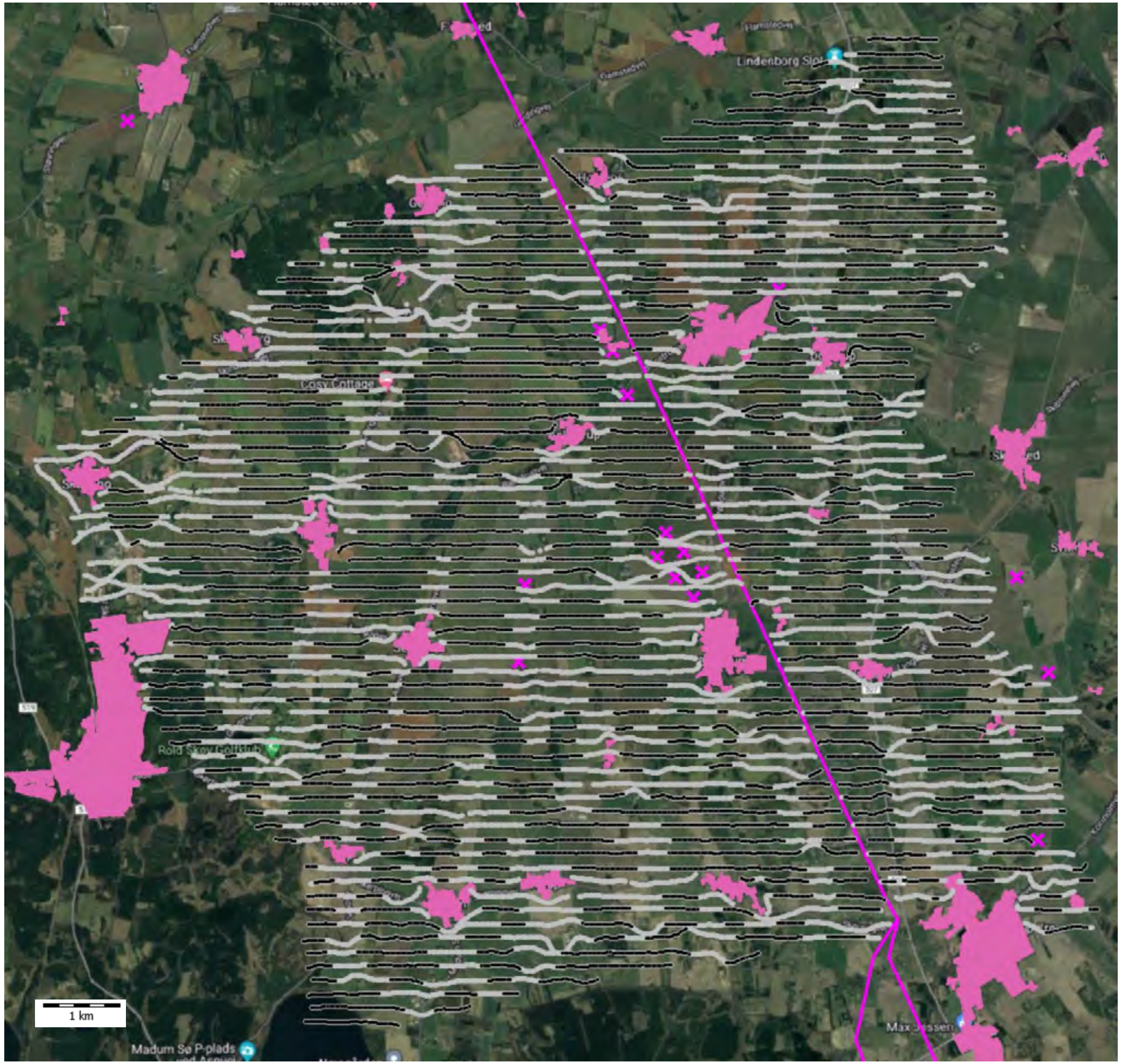
120 100 80 60 40 20 0 -20 -40 -60 -80 -100 -120 -140 -160 -180 -200 -220 -240
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500

# Data – Gerda

**SkyTEM:**

- **Good in regions with high soil conductivity (e.g. clays).**
- **Large portion of raw data (grey) is deleted due to couplings.**
- **Unable to resolve thin/geographically limited layers.**



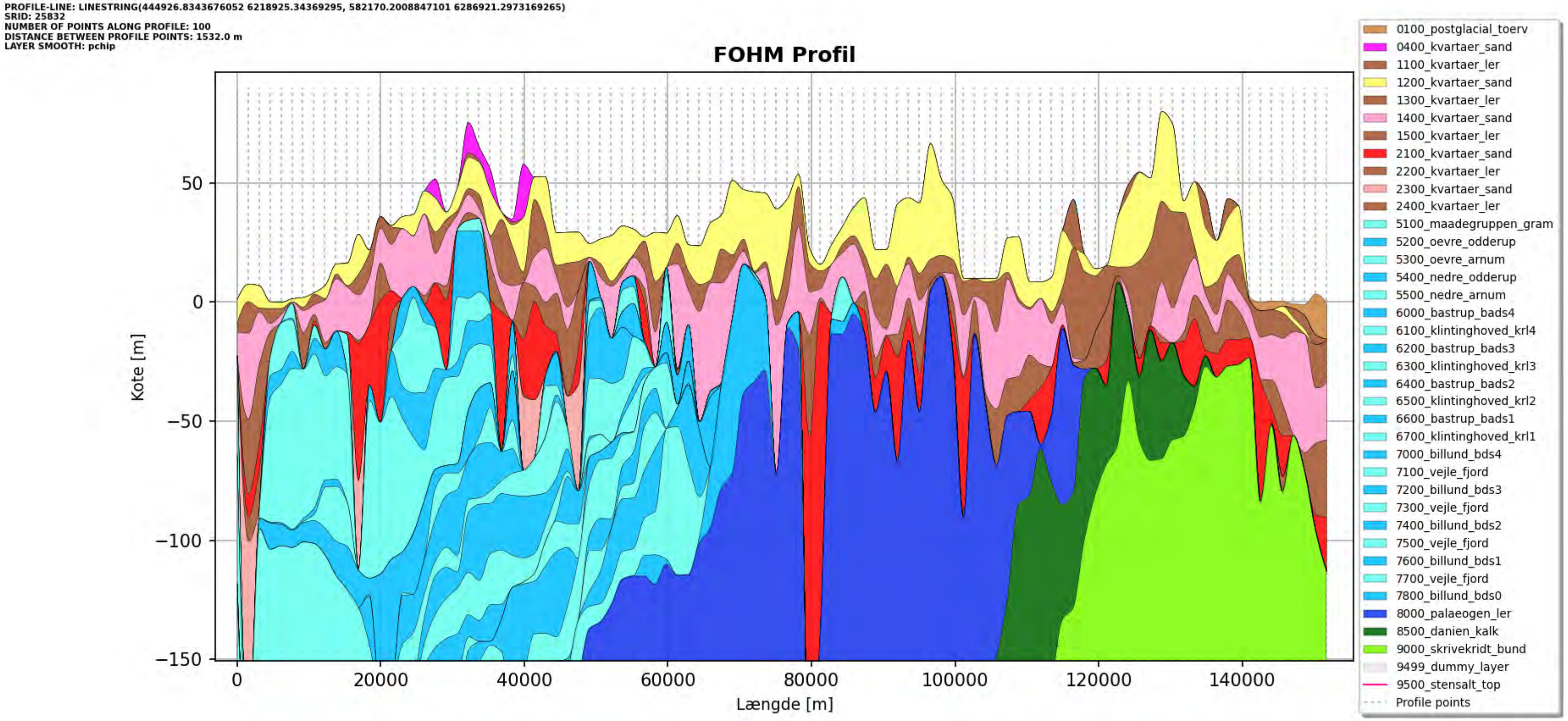
# Data – Existing models


FOHM:

Common public hydrostratigraphic model
May be less accurate at model boundaries

Model database:

Contains individual hydrostratigraphic and hydrologic models



# Surveys

Where are we missing information?
- How large is the area?
- Is it possible that data exists elsewhere?

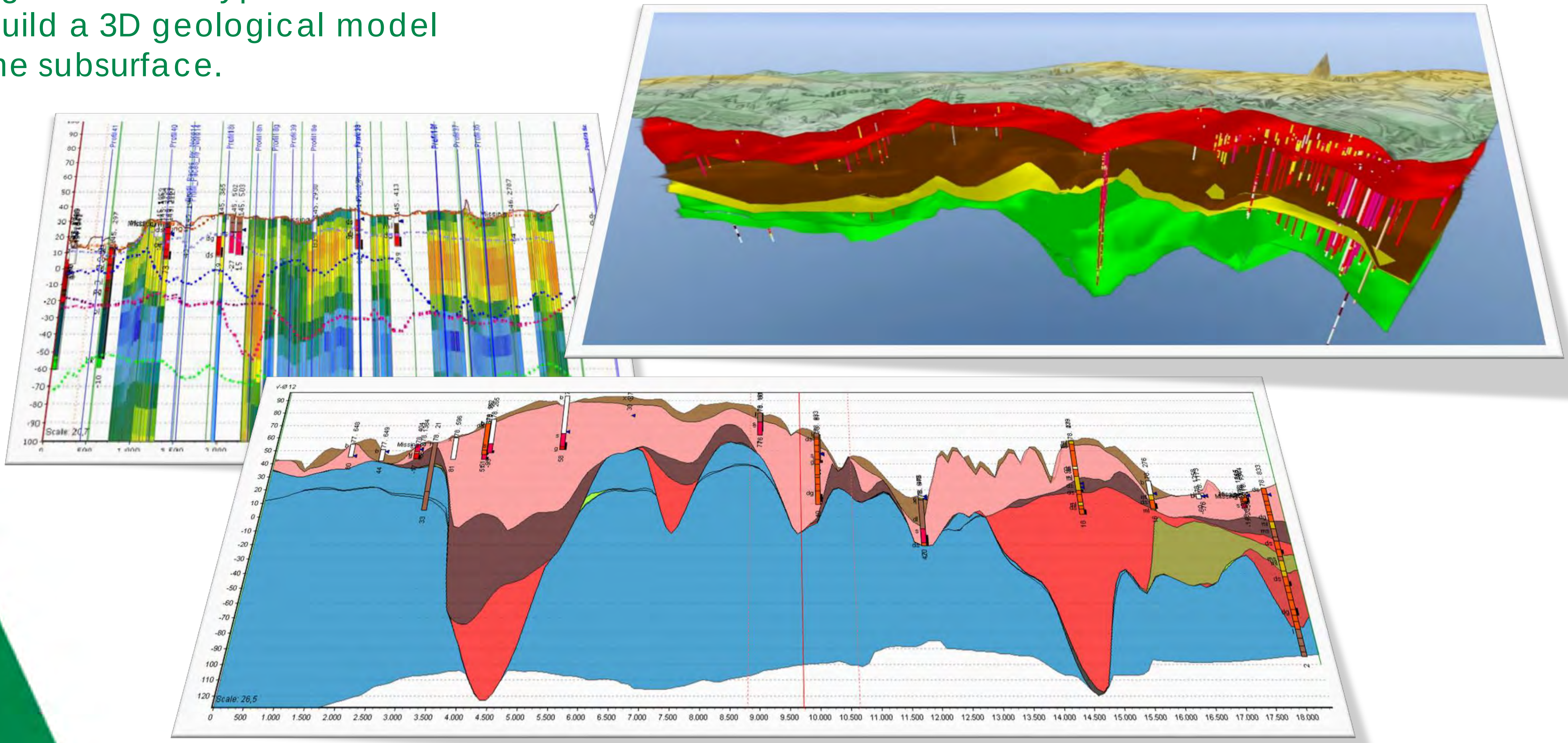
What kind of information do we need?
- Geophysics?
- Water chemistry?
- Water level measurements?

For geophysics: Which method should be used?
- What is the target depth?
- What resolution do we need?
- What kind of geology do we expect?

Formalities:
- Notification of citizens (e.g. by phone calls, electronic post, newspaper adverts)
- Time of year (e.g. boreholes may be closed during the winter)

# Geological Modelling

Integration of all types of data to build a 3D geological model of the subsurface.

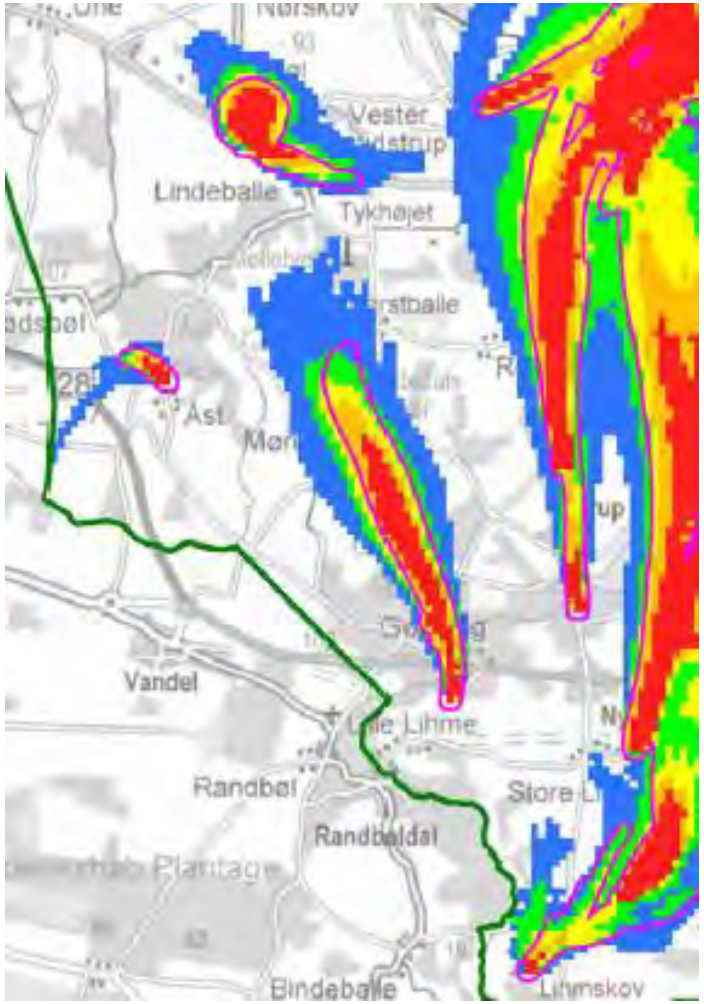


# Hydrological Modelling

Build model to simulate surface water flow and groundwater flow

Simulate and predict aquifer conditions.

Delineate particle transport time up to 200 years, with a 100 m buffer and 300 m around wells.



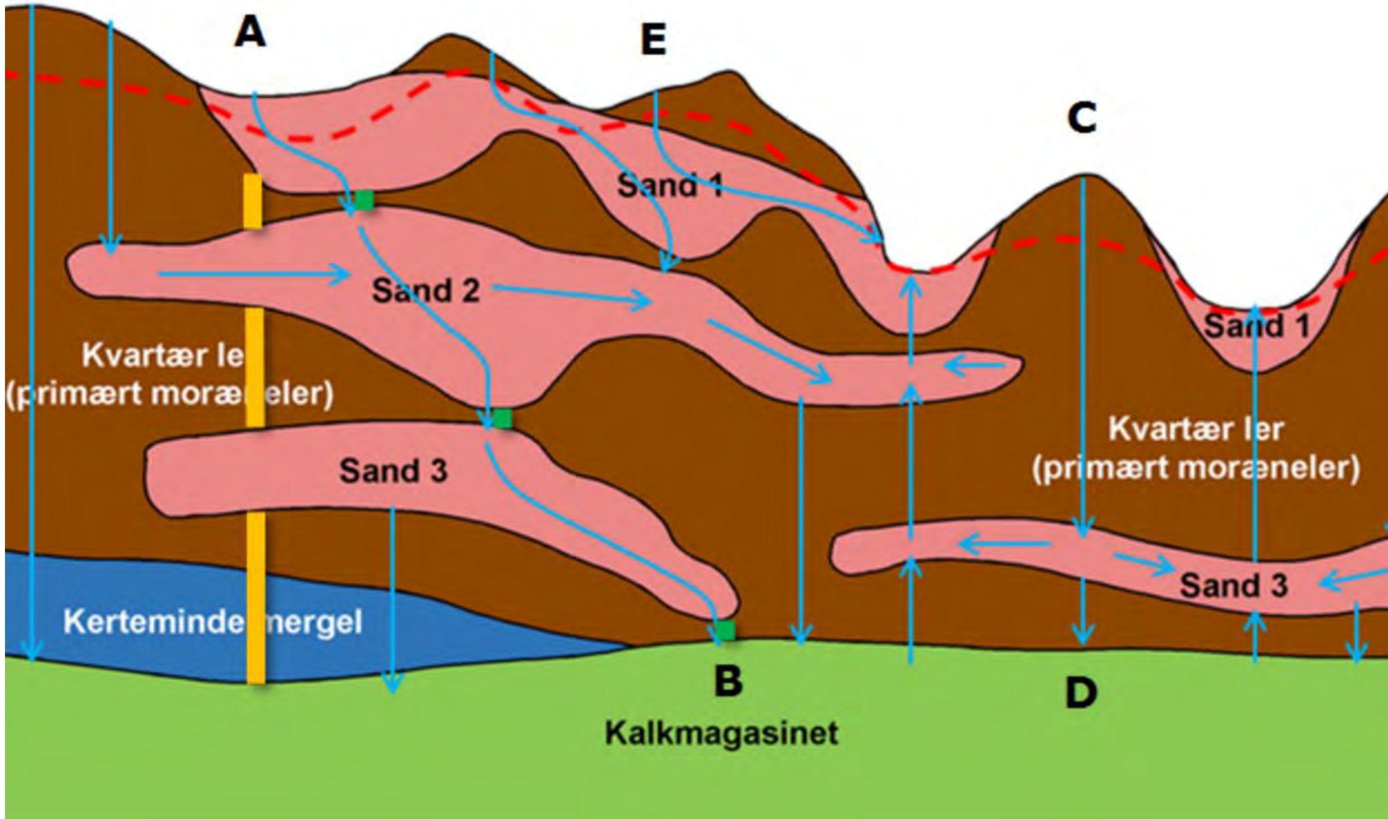

# Vulnerability Assessment

Designation applied to

- Selected drinking water areas (OSD) – Future groundwater resource
- Catchment areas for waterworks/utilities outside OSD

Zonation guide: detailed description of how to delineate areas vulnerable to nitrate

How to decide where action is needed: municipalities are responsible



# Vulnerability Assessment

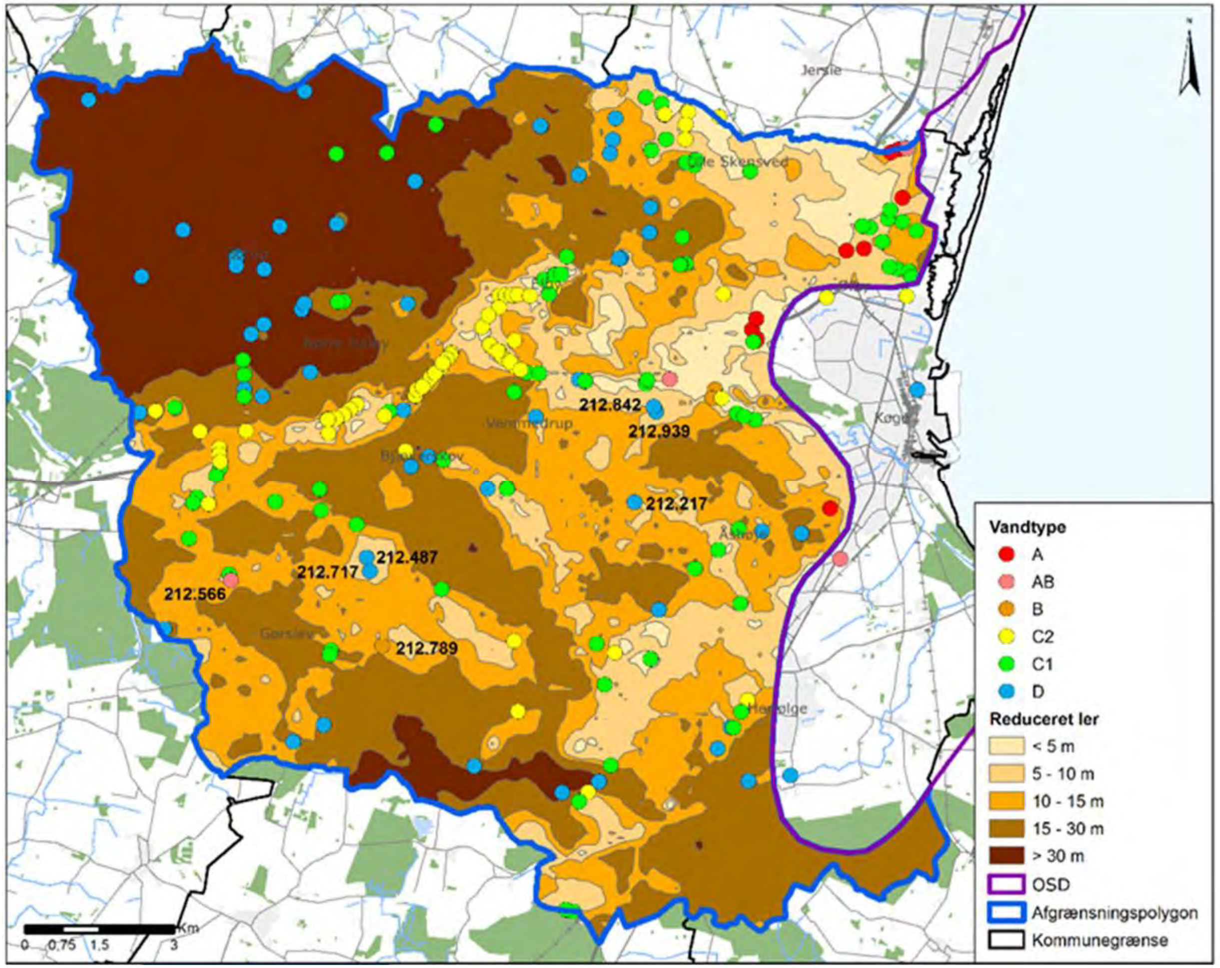
## Accumulated reduced clay thickness

- Thickness of clay is mapped
- Oxidation redox boundary is mapped
- Resulting in thickness of reduced clay above relevant aquifer

## Water Chemistry

- Water type – does it match our expectations?
- Nitrate concentrations
- Iron, Ammonium and methane

Evaluate case by case, area by area

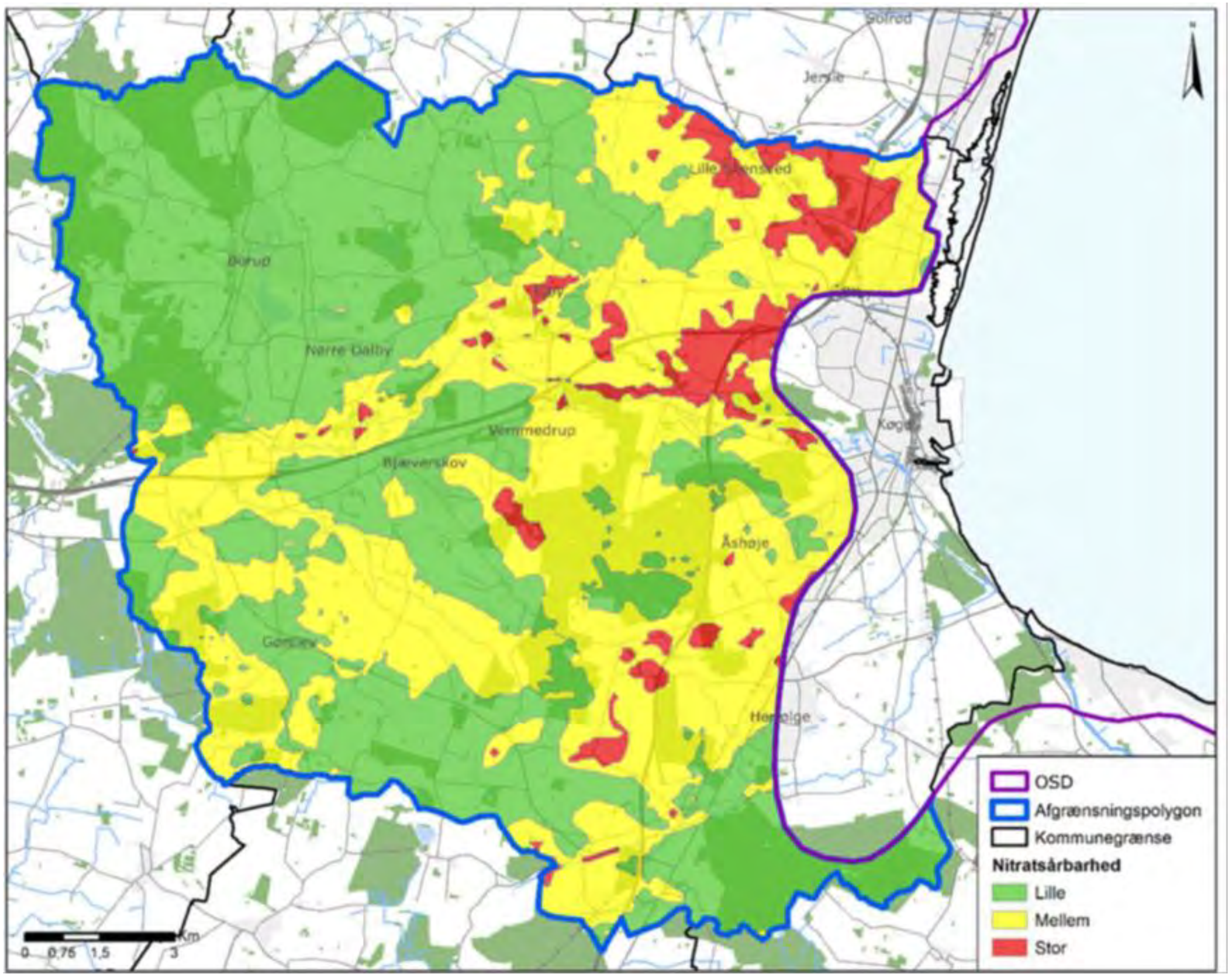


# Vulnerability Assessment

What is above the aquifer | Water type

| Nitrate vulnerability | Properties of aquifers and cover layers | Groundwater quality |
|---|---|---|
| **Low** | - Cover layer is fine-grained, gray clay or mica clay OR<br>- Cover layer has a high organic content, e.g. lignite OR<br>- **Thickness of reduced (gray), coherent clay cover layers is more than 15m** OR<br>- Aquifer is reduced rock containing organic material, pyrite, and possibly lignite. | Groundwater from methane zone and iron- and sulfate-zone.<br>**Water type C and D.** |
| **Medium** | - Cover layer is oxidized sand with lenses of silt and clay OR<br>- Cover layer is reduced, gray sand or gray/gray-black sand containing lignite or pyrite OR<br>- **Thickness of reduced (gray) coherent clay cover layers is 5 – 15m** OR<br>- Aquifer is reduced rock. | Groundwater from iron- and sulfate-zone.<br>**Water type C.** |
| **High** | - Only cover layer of oxidized, yellow-brown sand and/or clay OR<br>- **Thickness of reduced (gray) coherent clay cover layers is less than 5m** OR<br>- Aquifer has no significant nitrate reduction potential. | Groundwater from oxygen- and nitrate-zones.<br>**Water type A and B.** |

# Vulnerability Assessment



# Partners and Cooperation

GEUS and universities:
Scientific research, development and databases

Water Utilities and water companies:
Water supply, water extraction (and voluntary landowner agreements)

Private consulting companies:
Perform practical mapping for the EPA

# Key Takeaways

Research, methods and standards developed over +20 years for mapping and protecting groundwater

Public primary data and databases, easy accessible

Public interpreted data, easy accessible

State of the art data collection methods: SkyTEM, tTEM and more

Specialized software: GeoScene3D and Aarhus Workbench and more

Close collaboration between public institutions and private companies

# Thank you for your attention!


Developments after the completion of the national groundwater mapping
Esben Auken, CEO, adjunct professor
TEMcompany Aps, Aarhus University

# Content

- Background
- Software and system research and innovation
- The geophysics hub around Aarhus
- Some thoughts

# The hydrogeophysics hub in the Aarhus Area

# Background for GeofysikSamarbejdet

- GeofysikSamarbejdet – HydroGeophysics Group – Aarhus University
- Supporting national campaign, develop methods, software, standardization, guidelines, support contractors
- Education of geologists and hydrogeologists in geophysical methods
- Voluntarily supported by the counties, 4 – 6 positions/year
- GERDA, SkyTEM Aarhus Workbench came out of this
- HGG involvement faded after EPA took charge in 2007 –with a gradual decrease until 2015
- Last involvement by HGG in 2020

# Background for GeofysikSamarbejdet

GeofysikSamarbejdet (HGG)

Supporting national campaign, develop methods, software, standardization, guidelines, support contractors

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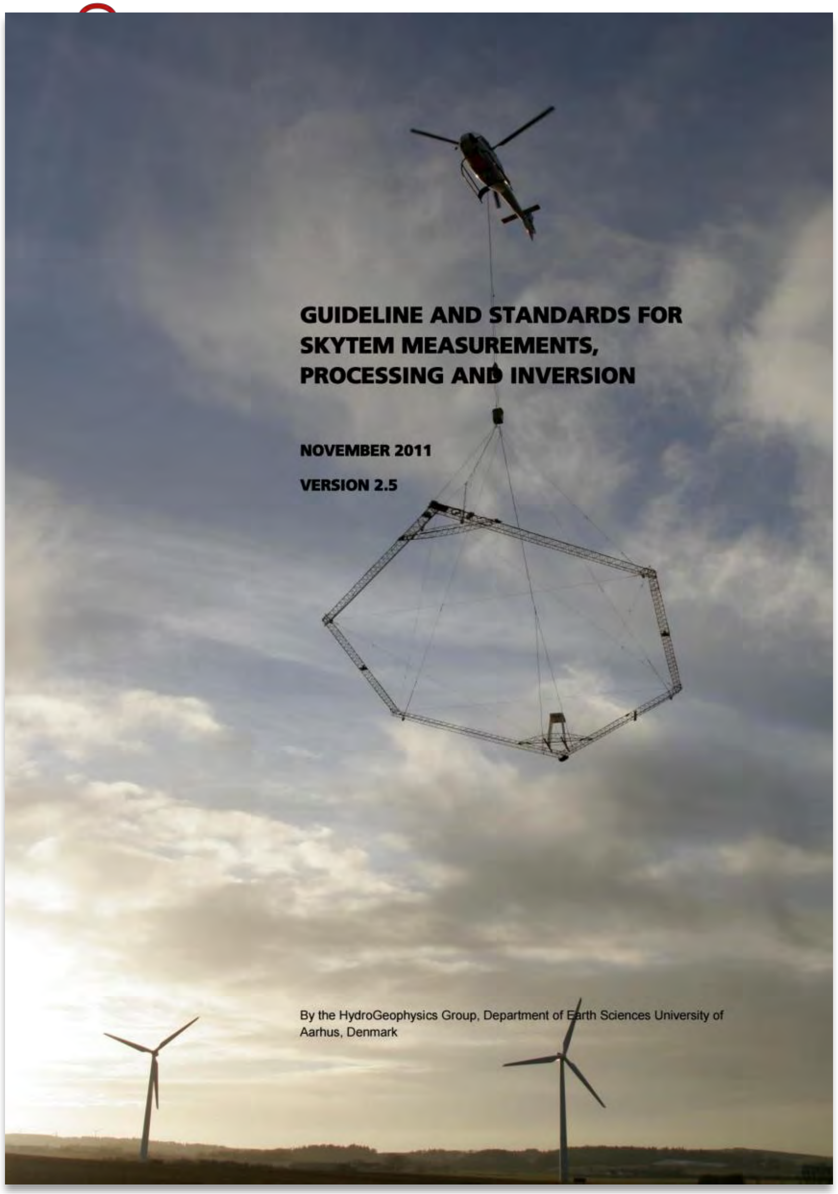
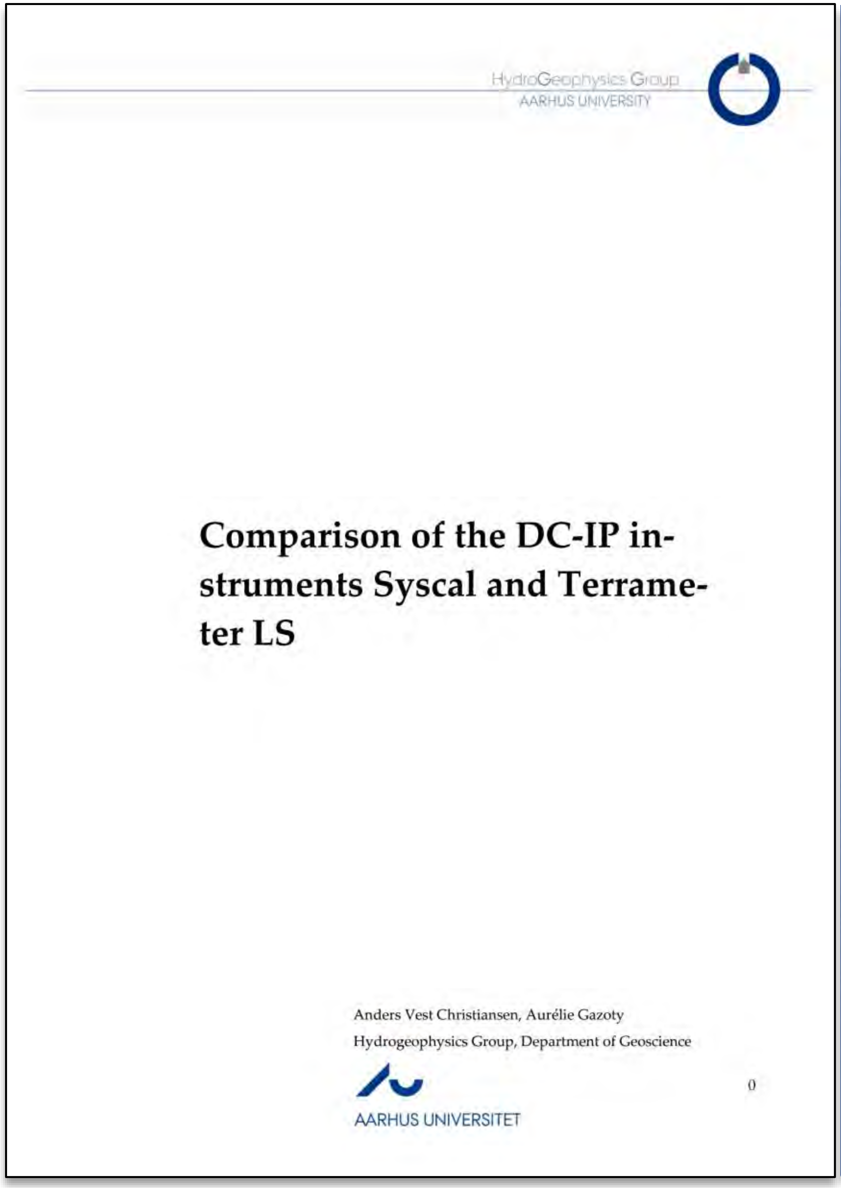
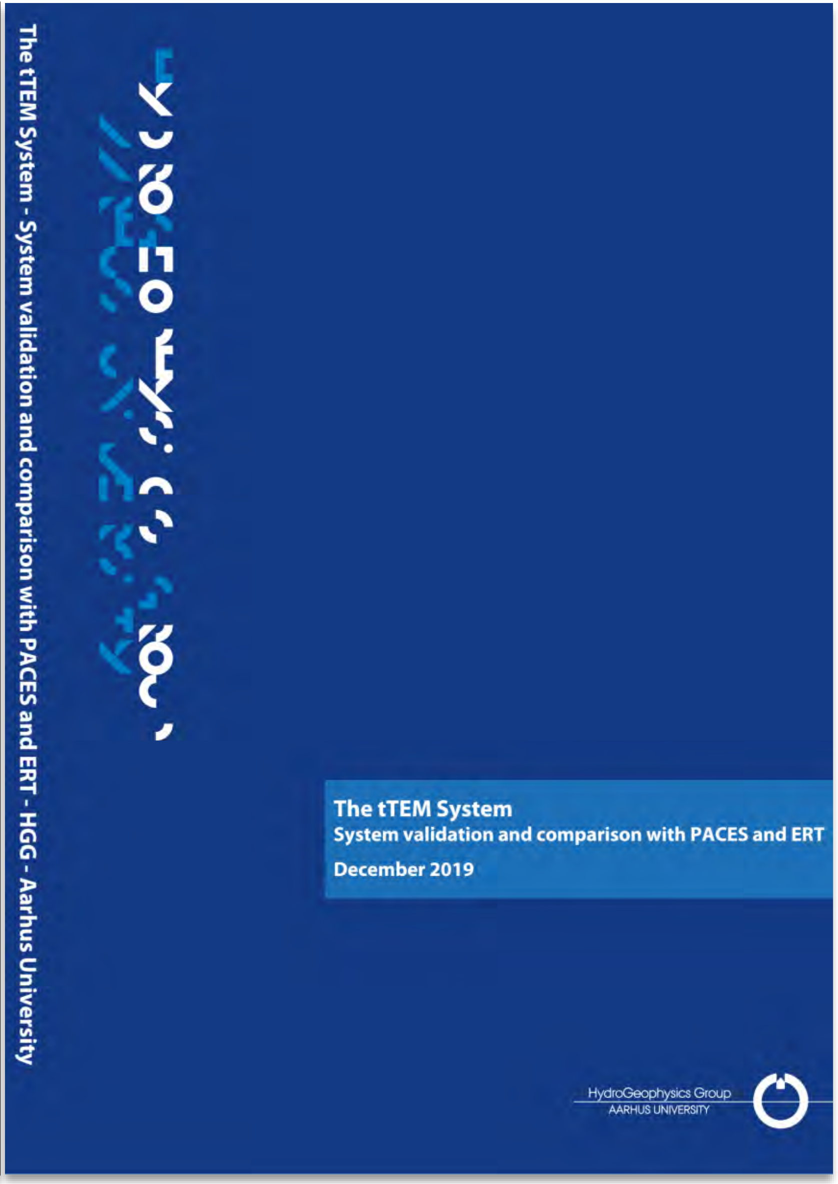
# Reports


GUIDELINE AND STANDARDS FOR SKYTEM MEASUREMENTS, PROCESSING AND INVERSION
NOVEMBER 2011
VERSION 2.5
By the HydroGeophysics Group, Department of Earth Sciences University of Aarhus, Denmark


HydroGeophysics Group
AARHUS UNIVERSITY
Comparison of the DC-IP instruments Syscal and Terrameter LS
Anders Vest Christiansen, Aurélie Gazoty
Hydrogeophysics Group, Department of Geoscience
0
AARHUS UNIVERSITET


The tTEM System - System validation and comparison with PACES and ERT - HGG - Aarhus University
The tTEM System
System validation and comparison with PACES and ERT
December 2019
HydroGeophysics Group
AARHUS UNIVERSITY

# Background for GeofysikSamarbejdet

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- Supporting national campaign, develop methods, software, standardization, guidelines, support contractors
- Education of geologists and hydrogeologists in geophysical methods
- Supported by the counties, 4 – 6 positions/year

## Outcome

- Methods!
- SkyTEM, Aarhus Workbench, Data handling ect

.

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## GeofysikSamarbejdet (HGG)

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## Outcome

Methods!

SkyTEM, Aarhus Workbench, Data handling ect

## Environmental Protection Agency

HGG involvement faded after EPA became in charge 2007 – with a gradual decrease until 2015

# Instruments, research and Innovation

- PACES – Pulled Array Continuos Profiling, until ~2010
- ERT – Earth Resistivity Imagining, invented in Lund, ~1990
- 40x40 m TEM – transient electromagnetic –Protem47 by Geonics Ltd
- BøvTEM – SkyTEM prototype transmitter with the P47, ~2002
- SkyTEM – first measurements in 2002
- HGG WalkTEM ~2012

- tTEM – mapping of farm fields and point source contaminations, 2017
- sTEM –2023 – a HGG WalkTEM/Protem 47 type family instrument

# Technologies from GeofysikSamarbejdet

TEMcompany

## Instruments

Pulled Array Continuos Profiling, until ~2010
ERT – Earth Resistivity Imagining, invented in Lund, ~1990

40x40 m TEM – transient electromagnetic –Protem47 by Geonics Ltd
HP-TEM – SkyTEM prototype transmitter with the P47, ~2002
HGG WalkTEM ~2012

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Biludlejning


Tom Birch Hansen

# Technologies from GeofysikSamarbejdet

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## Airborne

SkyTEM – first measurements in 2002

## .



# Technologies from GeofysikSamarbejdet

TEMcompany

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HGG WalkTEM ~2012

## Airborne

SkyTEM – first measurements in 2002

## Post GFS

tTEM – mapping of farm fields and point source contaminations, 2017

sTEM -2023 – a HGG WalkTEM/Protem 47 type family instrument

# tTEM

# Software, research and innovation

- Software hardly existed in 1999!!
- AarhusInv gradually developed as the inversion code
- Aarhus Workbench began with a vison to integrate all data in a common platform, started with making importers
- SkyTEM inversion ~2004
- PACES inversion ~2000
- ERT inverted with Res2inv from the start
- Later automatic hydro stratigraphical models, never used by EPA

# Software, research and innovation

Software hardly existed in 1999!

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# Software, research and innovation

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Software

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SkyTEM inversion ~2004

PACES inversion ~2000

ERT inverted with Res2inv from the start

Hydro stratigraphical models, never used by EPA

# Funding enables Research and Innovation

- GeofysikSamarbejdet until ~2015
- Surveys in Denmark with 40x40 m TEM, PACES, SkyTEM
- World wide projects with SkyTEM: Galapagos, Mayotte, Yellowstone, Holland ect.,

- Innovation Found Denmark, Højteknologi Fonden, Grundfos fonden, starting from ~2010
- Interreg and other EU

- In 2020 we were 30 researchers in HGG

# Companies and the hub in Aarhus

- **SkyTEM Surveys Aps in 2003, system for water**
  - Slowly gained marked with new frame system, higher transmitter moments and highly increased production
  - SkyTEM has today about 50% of the world marked for AEM
  - ~80 employees, offices in Canda, USA, SA and Australia

- **Aarhus GeoSoftware Aps in 2015**
  - Aarhus Workbench and Res2Dinv/Res3Dinv from 2017. Has gained reputation as a reliable tool worldwide for AEM and ERT
  - Acquired by Seequent in 2021
  - ~10 employees in 2023

# Companies and the hub in Aarhus

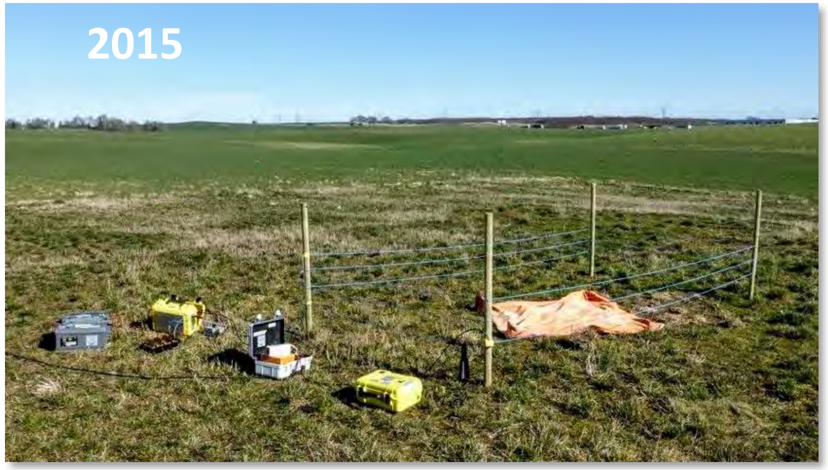
- **AarhusGeoInstruments Aps, now TEMcompany Aps, 2020**
  - Instrument R&D, production and sales
  - tTEM and sTEM instruments and more instruments to come
  - Rapid expansion form investment by Poul Due Jensen|Grundfos Foundation
  - 5 employees in January 2023, now ~18 employees

# TEMcompany vision

- Create easy-to-use geoscanners for groundwater exploration
- Mitigating the worldwide groundwater problems caused by the climate crises

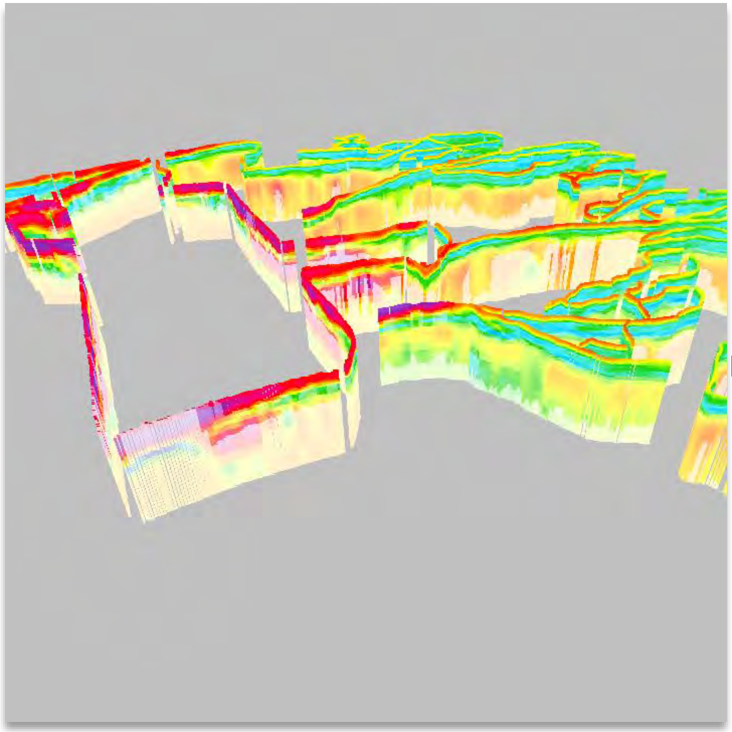
# TEMcompany history

- **2015**: Started to develop tTEM at Aarhus University
- **2020**: Aarhus GeoInstruments, a spin out with tTEM as main product
- **2023**: Investment from the Grundfos Foundation makes us rethink the company vision and enables us to think big 😊
- **Now**: 18 employes and very ambitious R&D, production and sales program






# Locating drinking water wells

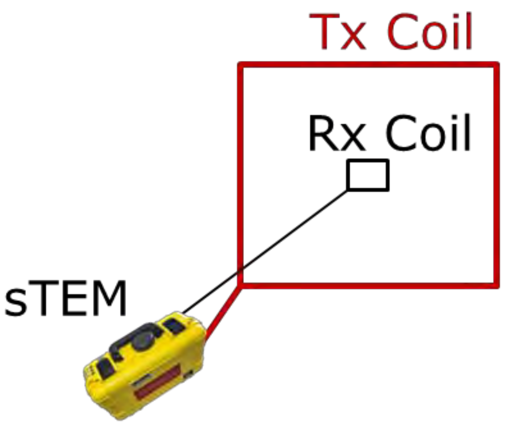


# tTEM in Kenya

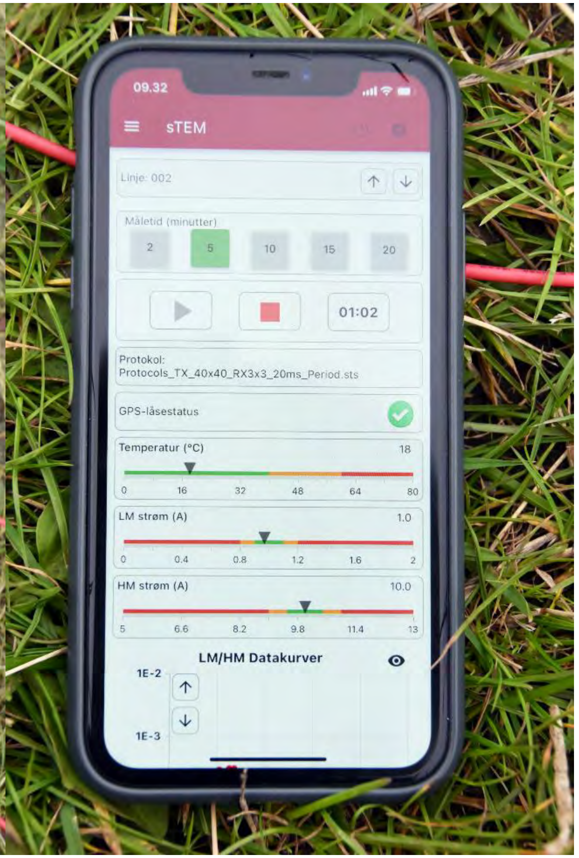
- Groundwater for small villages

TEMcompany

# sTEM control app (Android/IOS)



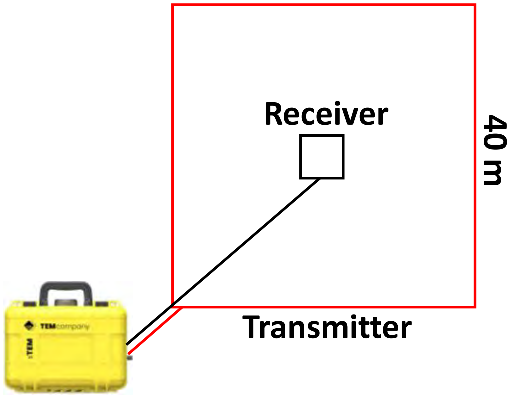


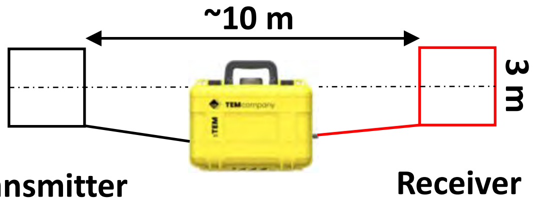
# sTEM in Kenya

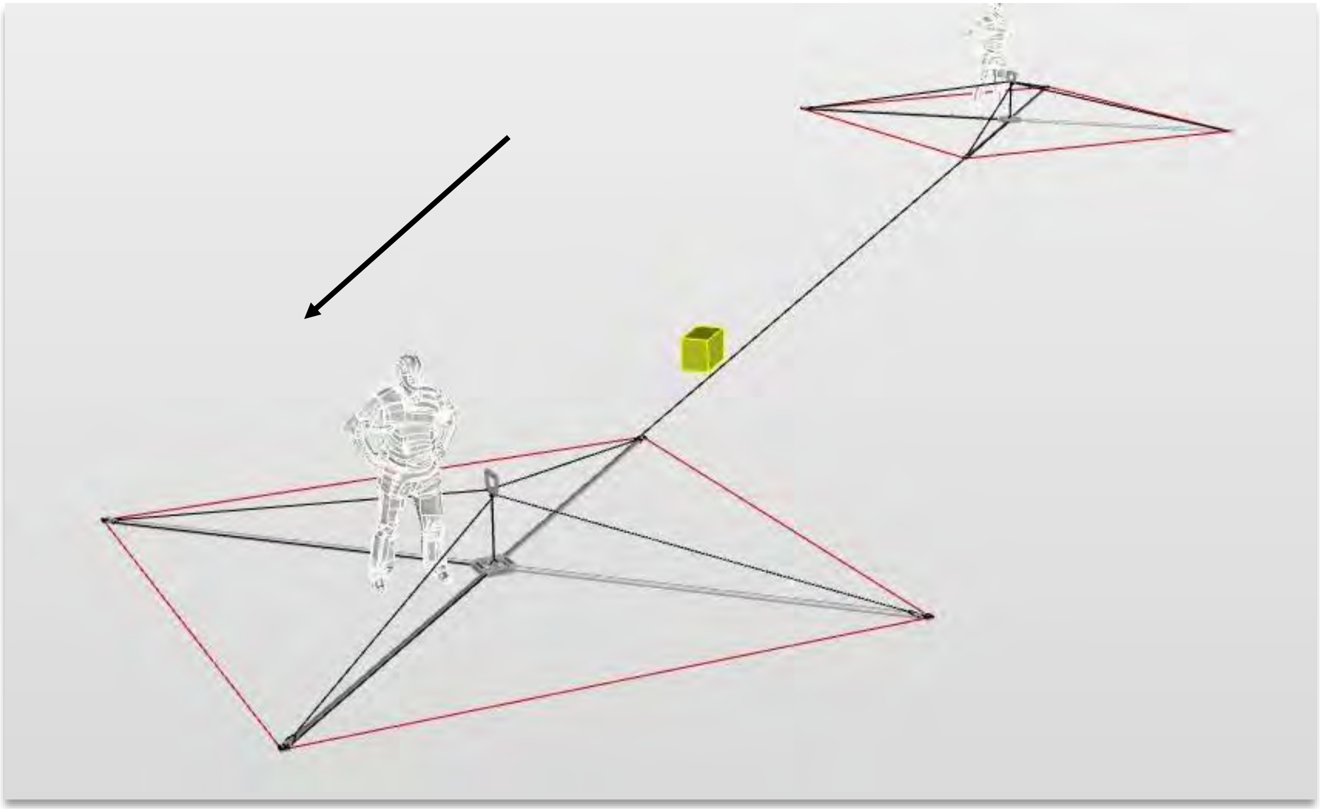
# sTEM family transmitter system

## Central loop




## Offset small loop



# Companies and the hub in Aarhus

- **Rambol, VSP, NIRAS, Covi**
- **Customers:  EPA, municipalities and waterworks**

- **Ramboll and VPS are operating SkyTEM and tTEM in international projects**

- **Past startups**
  - WaterTEC startup and merged
  - Dansk Geofysik startup and merged

# So, what came out of it?

- Groundwater resources in Denmark is well mapped and managed!
- A world leading hydrogeophysics hub centered around the research and innovation environment at the university
- Several new companies exporting the technology
- Several global consulting companies selling the technology worldwide
- Thank you for listening!

# Overview of SGU:s groundwater mapping with SkyTEM and other methods

**Peter Dahlqvist,** SGU (Geological Survey of Sweden) 2023-11-14

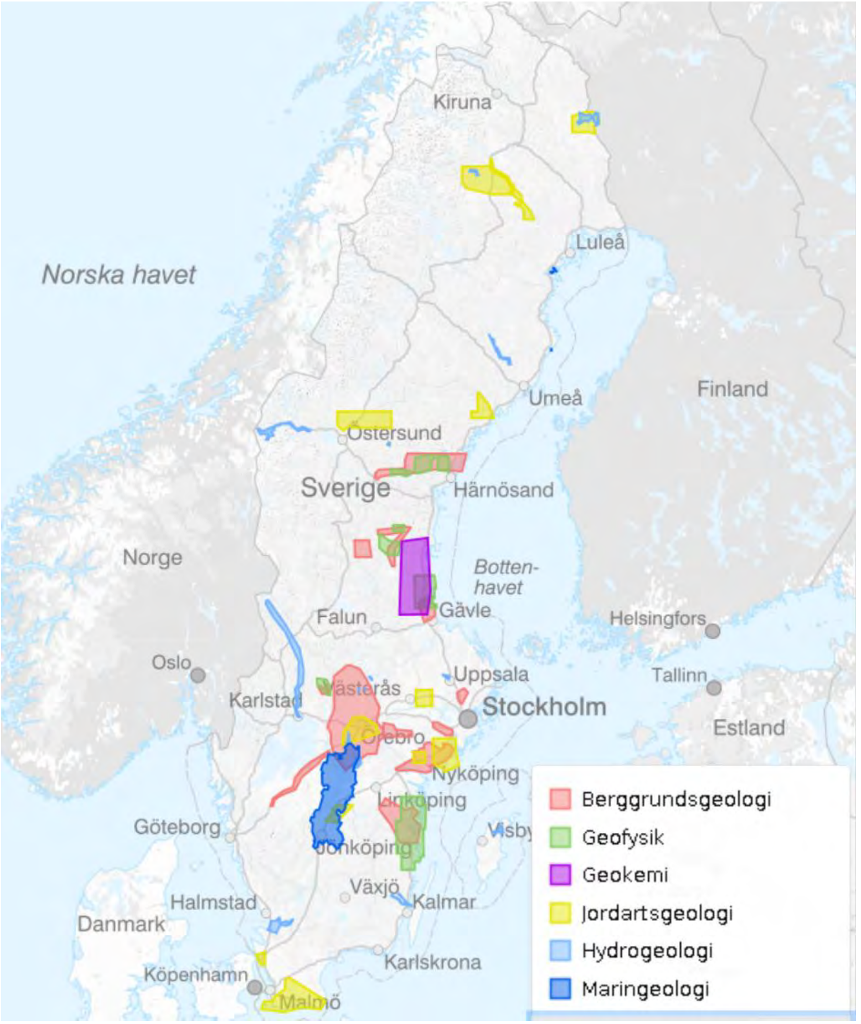
# SGU – groundwater mapping

Why ?

- national agency responsible for issues concerning rock, soil and groundwater in Sweden
- mapping, environmental objectivs, groundwater managment

Where?

- GW shortage areas
- Valuble GW-resources

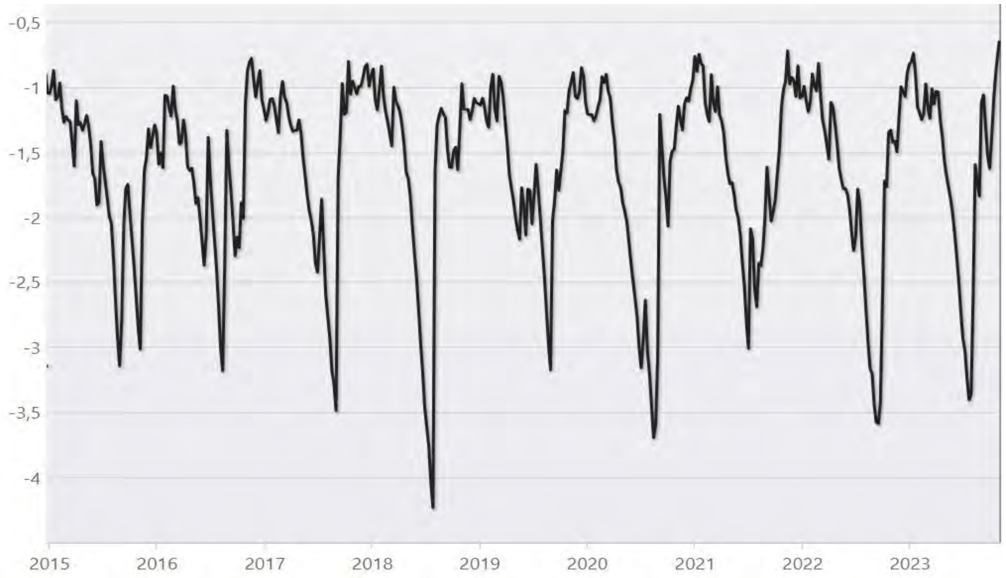


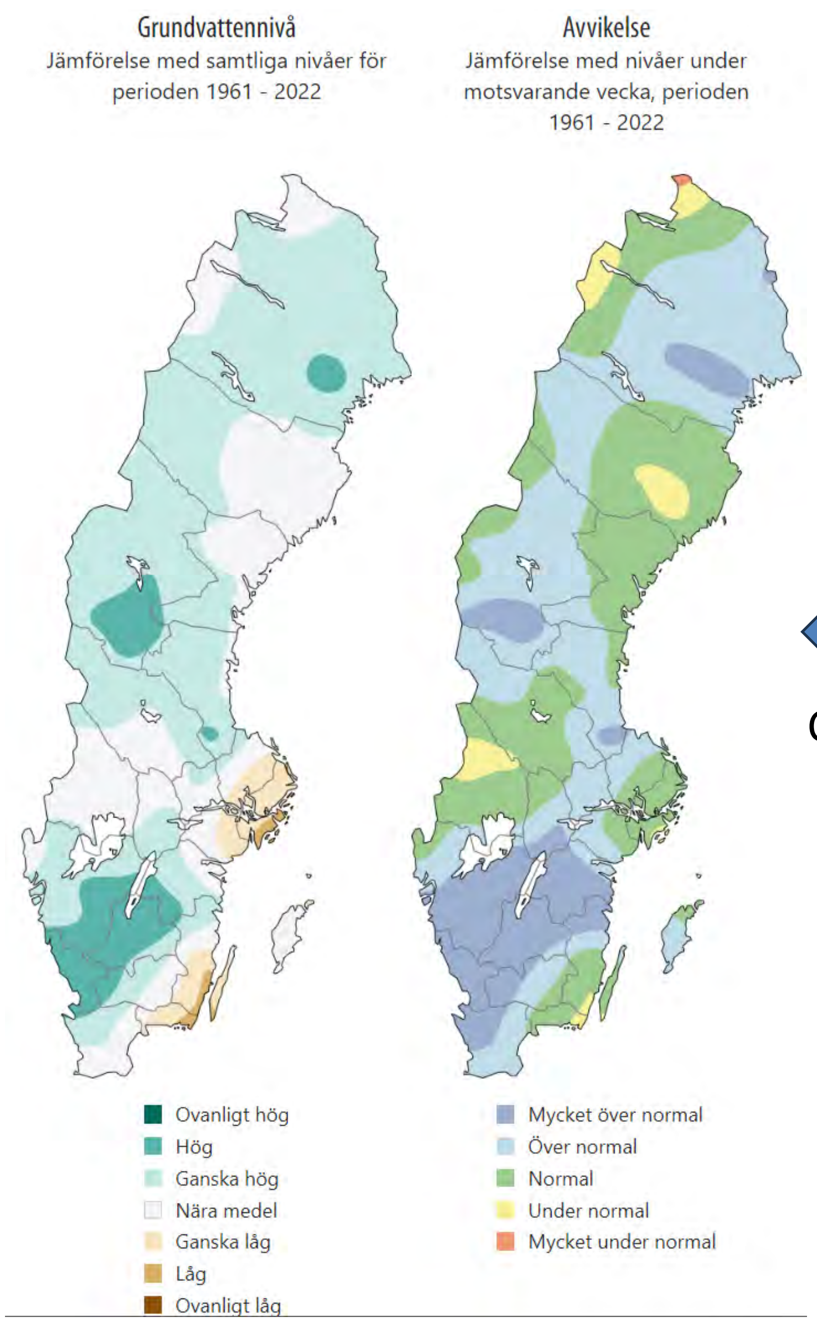
# SGU – groundwater mapping

- National monitoring of GW levels
- National monitoring of GW quality
- Local surveys of aquifers
- SkyTEM-mapping

# National monitoring of groundwater levels

[Kartvisare och diagram för mätstationer (sgu.se)]

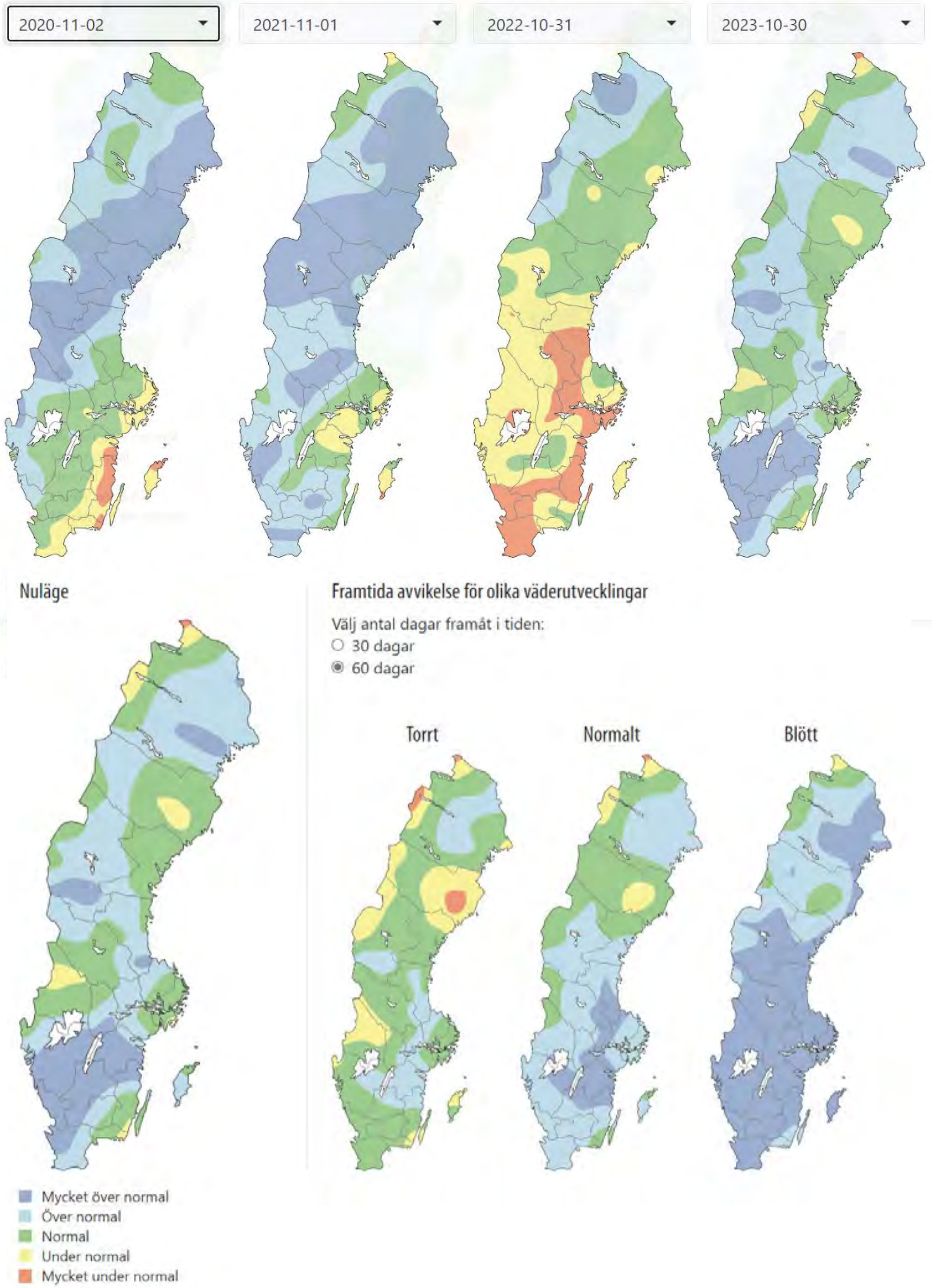



Earlier GW-levels

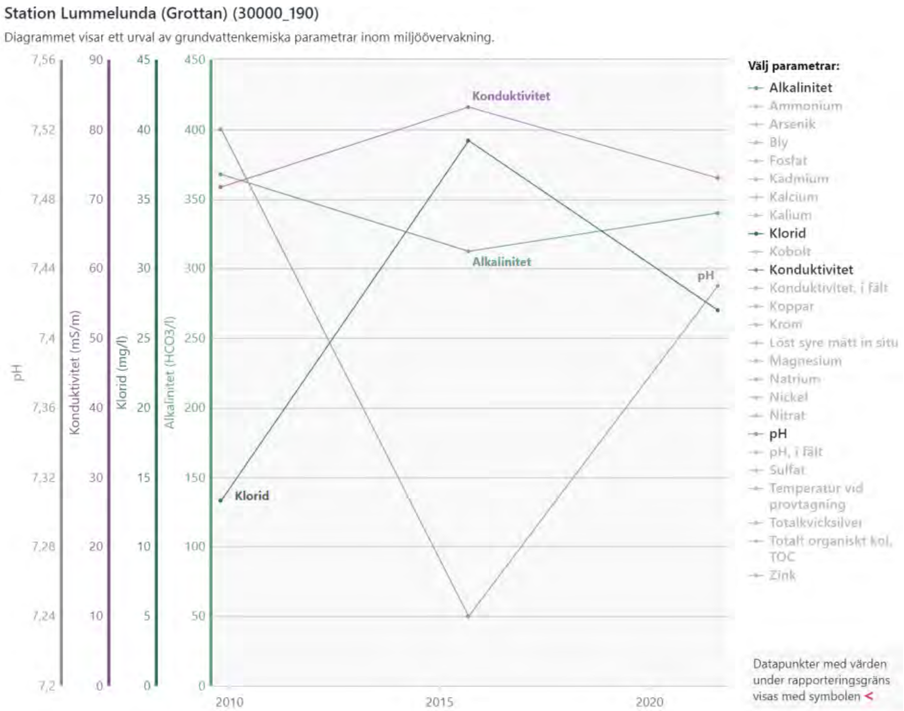
Current GW-levels

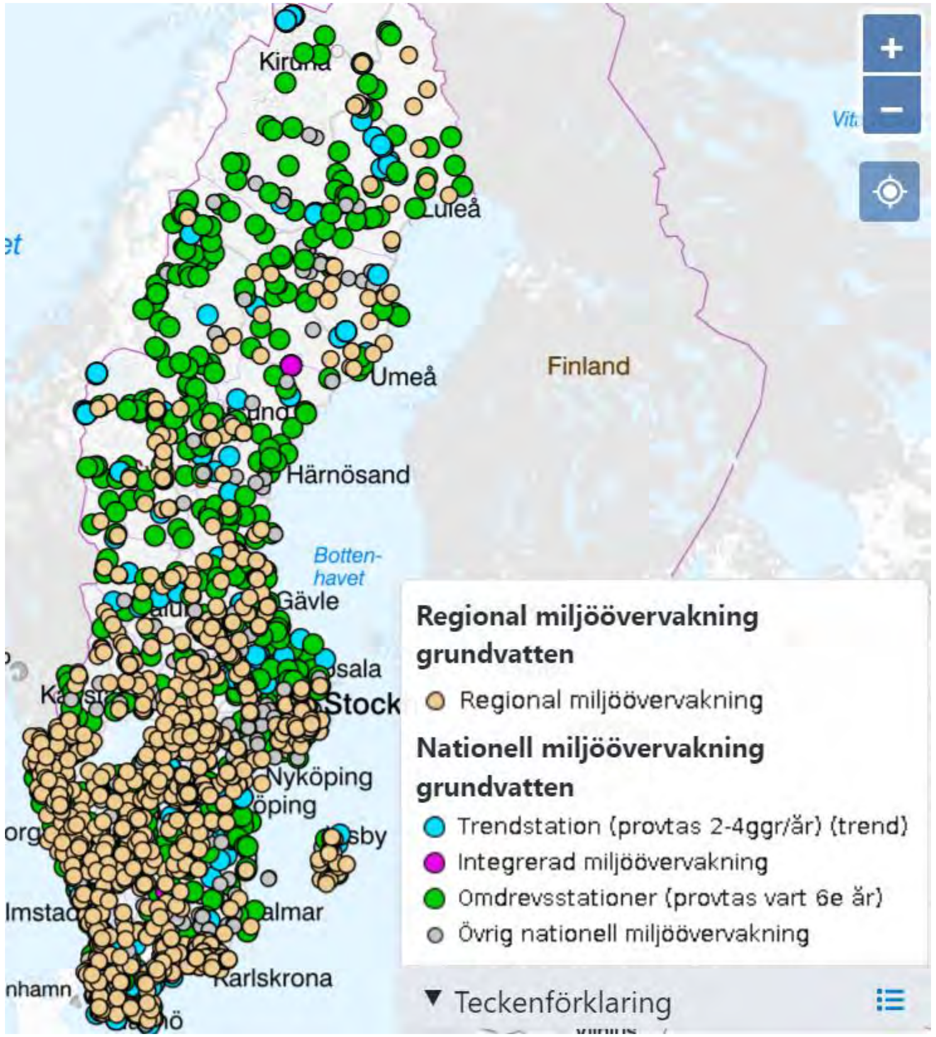
Future GW-levels



# National monitoring of groundwater quality

[Kartvisare och diagram för miljöövervakning av grundvattenkemi (sgu.se)](#)



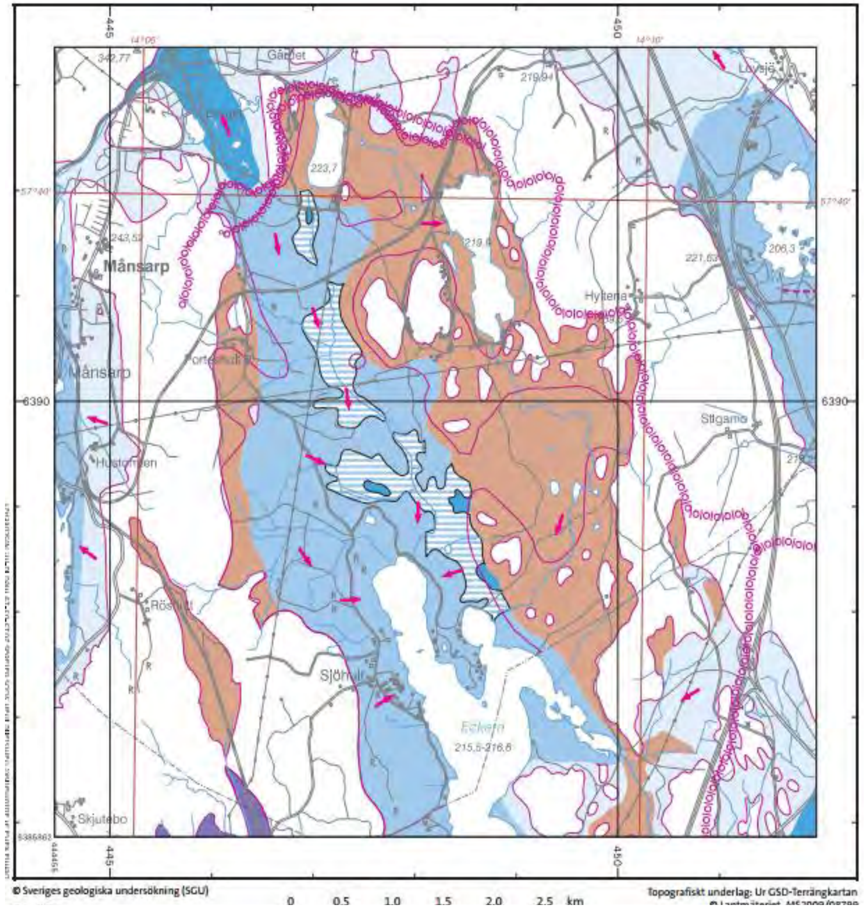




Next year national maps for ca 30 substances on the web [Bedömningsgrunder för grundvatten (sgu.se)](#)

# Local scale aquifer mapping (ca 20 reports/year)

- Groundwater investigations
- Drillings
- Geophysics (Seismics, ERT, RMT, Radar)
- Temperature spear
- Spring inventory

- Groundwater levels
- Flow directions
- Saturated zone
- Contact surface water
- Chemistry




# Groundwater mapping with SkyTEM in Sweden

Efter regeringsbeslut lyfter nu näringsminister Mikael Damberg (S) tillsammans med projektledaren Peter Dahlqvist med helikopter för att påbörja flygmätningarna och därmed börja kartlägga förekomsten av vårt viktigaste livsmedel, dricksvattnet. Bild: Björn Larsson Rosvall, TT

## Jakten på grundvatten görs från luften

SVERIGE Regeringen satsar 850 miljoner på tre år bland annat för att försöka säkra tillgången på grundvatten. Letandet efter nya grundvattentäkter är redan igång.

# Groundwater mapping with SkyTEM in Sweden

SkyTEM enables collection of large amounts of geological information in a short time.

The investigations result in improved data regarding soil depth, layer sequences, bedrock and the extent of the groundwater reservoirs in 3D.

In areas with water scarcity where the method works well.

The information can be used for water supply planning. Other applications are material supply, water protection areas, larger infrastructure projects and geological and hydrogeological research.

# Groundwater mapping with SkyTEM in Sweden

- Pilot area Skåne 2011
- Gotland (2013 & 2015)
- Öland (2016, MSB –financed, climate adaption)
- Halland (2017)
- Östergötland, Västergötland & Örebro  (2018)
- SW Skåne & W Blekinge/NW Skåne (2019)
- In total 6 000 km$^2$, ca 4 500 km$^2$ via ”grundvattensatsningen”.

# Groundwater mapping with SkyTEM in Sweden

The ”good example”

# Ny vattentäkt hittad på Fårö

18:30 | 16-06-30 Kommentera 2 Skriv ut TIPSA!

**VATTENKRISEN** Regionen har hittat en ny vattentäkt i Ava på Fårö. Redan i sommar kommer den nya vattentäkten att förse fåröborna med rent dricksvatten.

LÄS MER

27/7 VATTENKRISEN

**Krisläget: Bevattningsförbud över hela ön**

Därmed slipper regionen betala dyrt för att köra vatten med tankbil till Fårö.

– Faktum är att det är hundra gånger dyrare för oss att leverera vatten till Fårö jämfört med vad det kostar att leverera till Visby, säger maskiningenjören Lars Westerlund som jobbat mycket med vattenfrågan.

Enligt teknikförvaltningen ska kvaliteten på vattnet från Ava-täkten vara mycket bra.

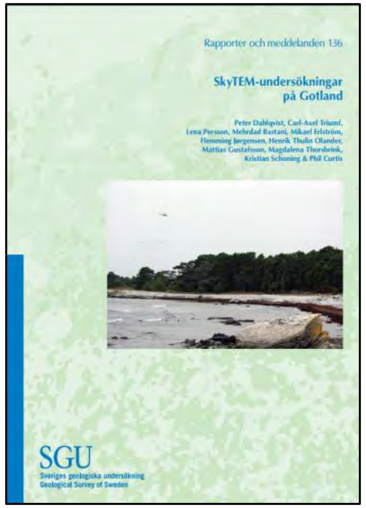
Både vattenkvaliteten och tillgången på vatten har under många år varit ett problem på Fårö, främst sommartid då invånarantalet ökar kraftigt.

För fyra år sedan flög Sveriges geologiska undersökningar (SGU) med helikopter över Fårö och hittade ett område som kunde tänkas innehålla rikligt med grundvatten. En provpumpning visade att det mycket riktigt fanns gott om vatten av god kvalitet. Nu har ytterligare tre hål borrats 40 meter ner i marken.

# Groundwater mapping with SkyTEM in Sweden

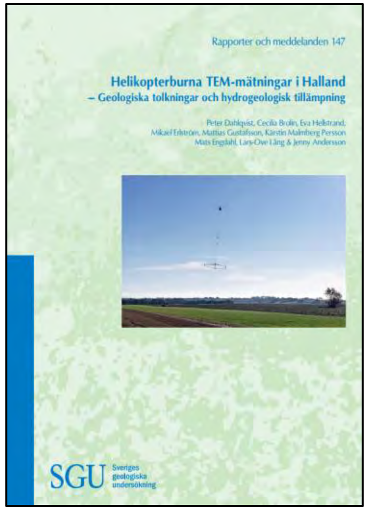

Slutrapport av FoU-projekt 35231
Kartläggning av hydrogeologiska förhållanden i sydsveriges sedimentära berggrund genom integrering av SkyTEM data med övriga geodatamängder
Peter Dahlqvist, Carl-Axel Triumf, Mikael Erlström, Mattias Gustafsson, Mehrdad Bastani, Niklas Juhojuntti, Mats Wedmark

Only internal report


Rapporter och meddelanden 136
SkyTEM-undersökningar på Gotland
Peter Dahlqvist, Carl-Axel Triumf, Lena Persson, Mehrdad Bastani, Mikael Erlström, Flemming Jørgensen, Henrik Thulin Olander, Mattias Gustafsson, Magdalena Thorsbrink, Kristian Schoning & Phil Curtis
SGU Sveriges geologiska undersökning Geological Survey of Sweden


Rapporter och meddelanden 140
SkyTEM-undersökningar på Gotland, del 2
Peter Dahlqvist, Carl-Axel Triumf, Lena Persson, Mehrdad Bastani, Mikael Erlström & Kristian Schoning
SGU Sveriges geologiska undersökning


Rapporter och meddelanden 145
SkyTEM-undersökningar på Öland
– Geologiska tolkningar och hydrogeologisk tillämpning
Peter Dahlqvist, Mehrdad Bastani, Lena Persson, Carl-Axel Triumf, Mikael Erlström, Mattias Gustafsson, Flemming Jørgensen, Mats Gulbrandsen & Kärstin Malmberg Persson
SGU Sveriges geologiska undersökning Geological Survey of Sweden


Rapporter och meddelanden 147
Helikopterburna TEM-mätningar i Halland
– Geologiska tolkningar och hydrogeologisk tillämpning
Peter Dahlqvist, Cecilia Brolin, Eva Hellstrand, Mikael Erlström, Mattias Gustafsson, Kärstin Malmberg Persson, Mats Engdahl, Lars-Ove Lång & Jenny Andersson
SGU Sveriges geologiska undersökning


Helikopterburna TEM-mätningar i Örebro län – Geologiska tolkningar och hydrogeologisk tillämpning
SGU


Helikopterburna TEM-mätningar vid Vätterns nordvästra strand
– Geologiska tolkningar och hydrogeologisk tillämpning
Peter Dahlqvist, Oskar Henriksson, Otto Pile, Lars-Ove Lång, Åsa Lindh, Mattias Gustafsson, Virginie Leroux & Jenny Andersson
SGU-rapport 2020:24
SGU


Helikopterburna TEM-mätningar över Östgötaslätten
– Geologiska tolkningar och hydrogeologisk tillämpning
Peter Dahlqvist, Oskar Henriksson, Jonas Ising, Mikael Erlström & Mattias Gustafsson
SGU-rapport 2020:33
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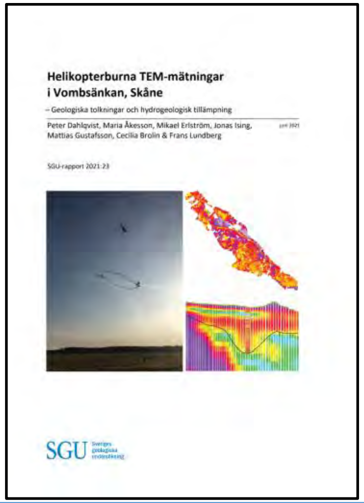
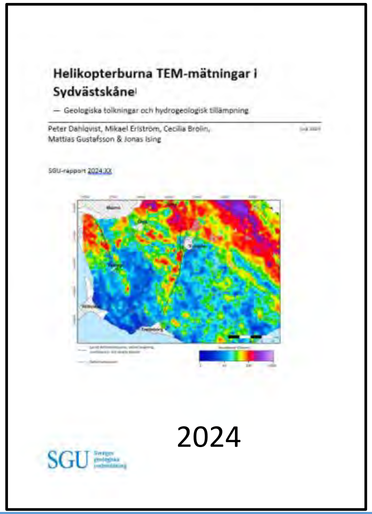

Helikopterburna TEM-mätningar i Vombsänkan, Skåne
– Geologiska tolkningar och hydrogeologisk tillämpning
Peter Dahlqvist, Maria Åkesson, Mikael Erlström, Jonas Ising, Mattias Gustafsson, Cecilia Brolin & Frans Lundberg
SGU-rapport 2021:23
SGU


Geologisk och hydrogeologisk tolkning
Helikopterburna TEM-undersökningar över Nordöstra Kristianstadsslätten och Listerlandet
november 2021
Peter Dahlqvist, Eva Hellstrand, Mikael Erlström, Mattias Gustafsson, Jonas Ising & Cecilia Brolin
SGU-rapport 2021:30
SGU


Helikopterburna TEM-mätningar i Sydvästskåne
— Geologiska tolkningar och hydrogeologisk tillämpning
Peter Dahlqvist, Mikael Erlström, Cecilia Brolin, Mattias Gustafsson & Jonas Ising
SGU-rapport 2024:XX
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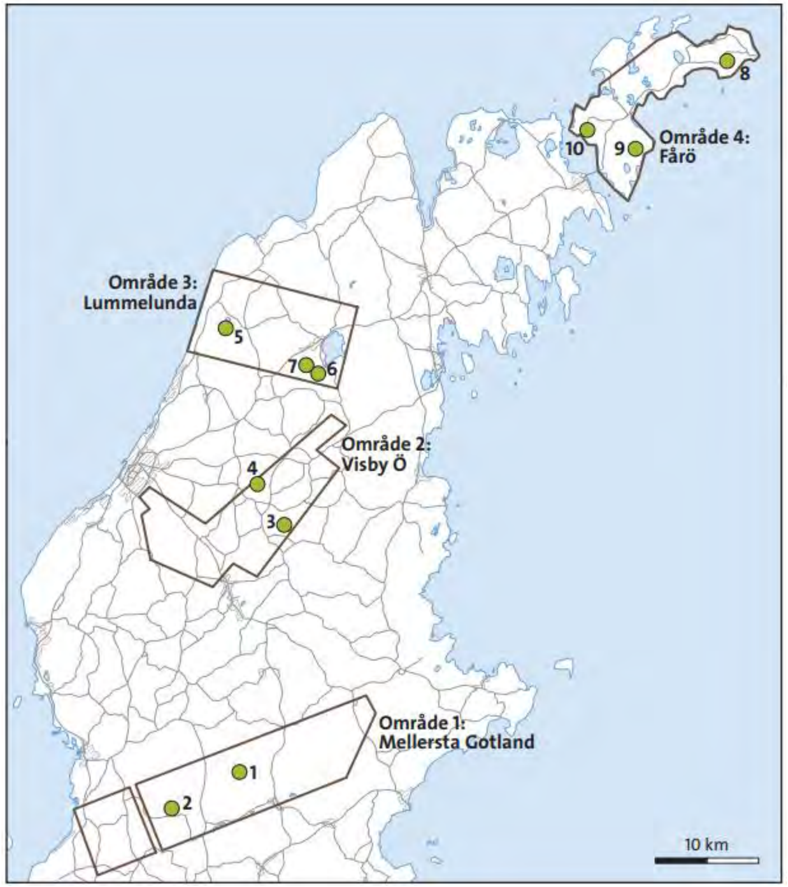
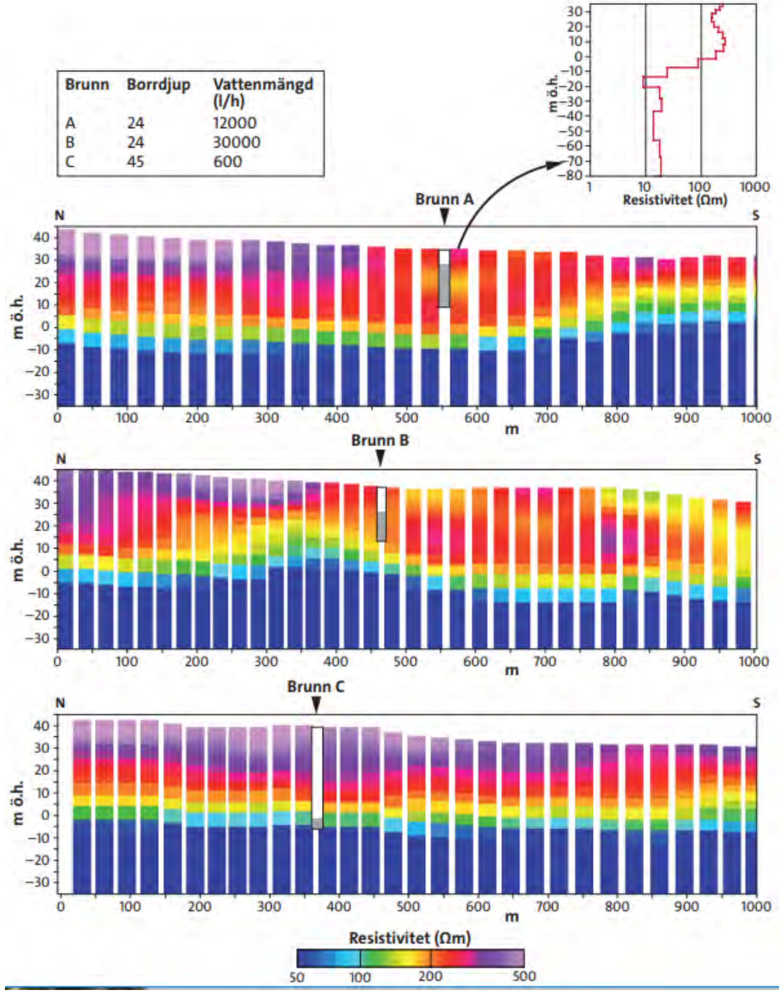
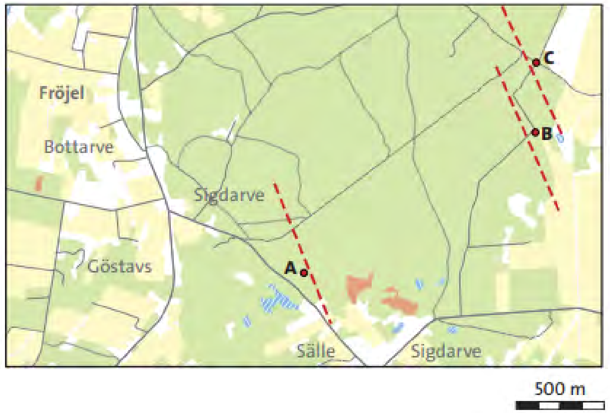
2024

# Groundwater mapping with SkyTEM – Gotland 2013

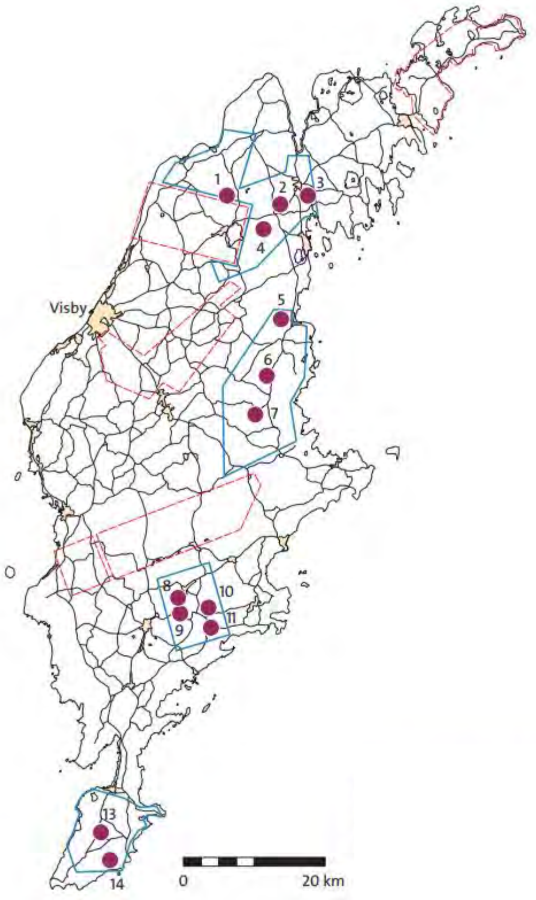


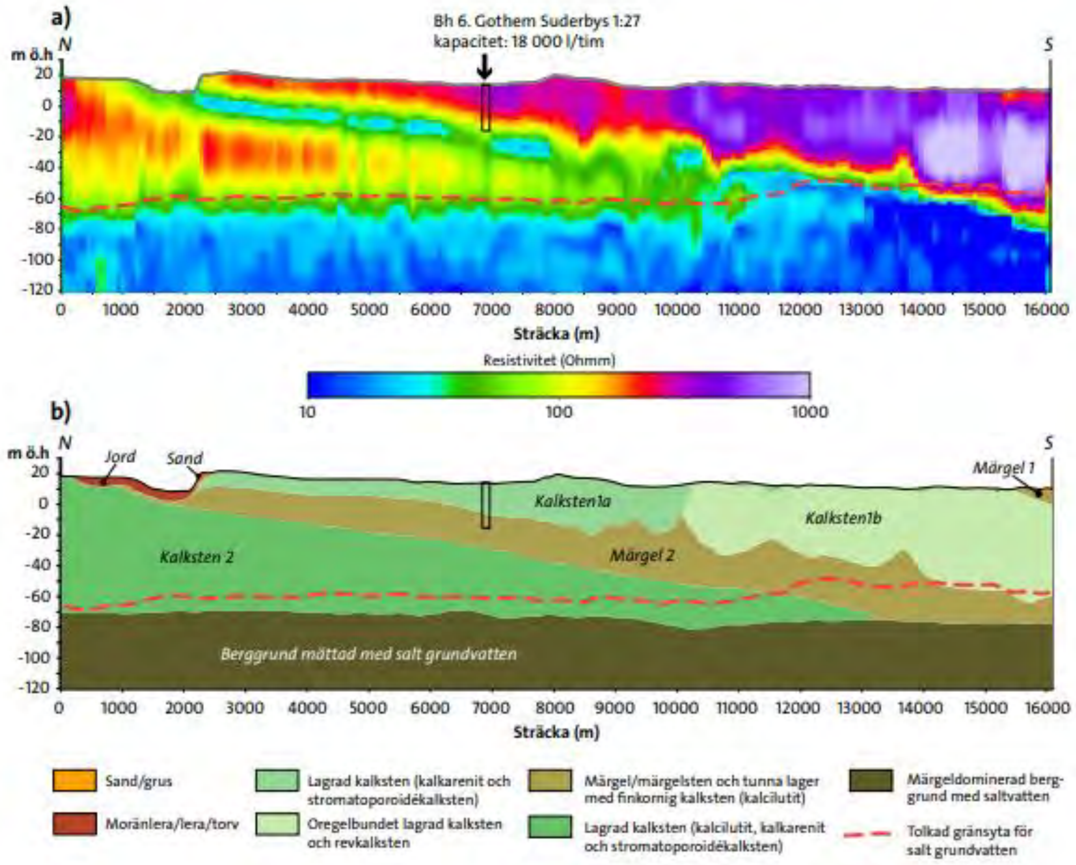




| Brunn | Borrdjup | Vattenmängd (l/h) |
|---|---|---|
| A | 24 | 12000 |
| B | 24 | 30000 |
| C | 45 | 600 |

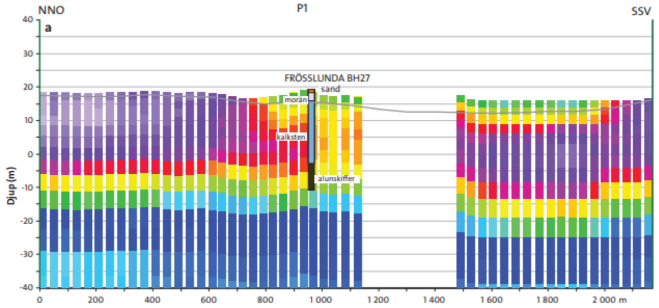


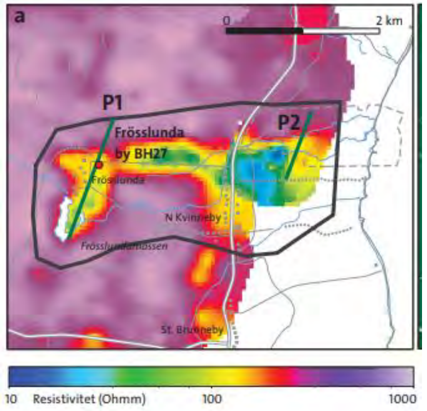
# Groundwater mapping with SkyTEM – Gotland 2015

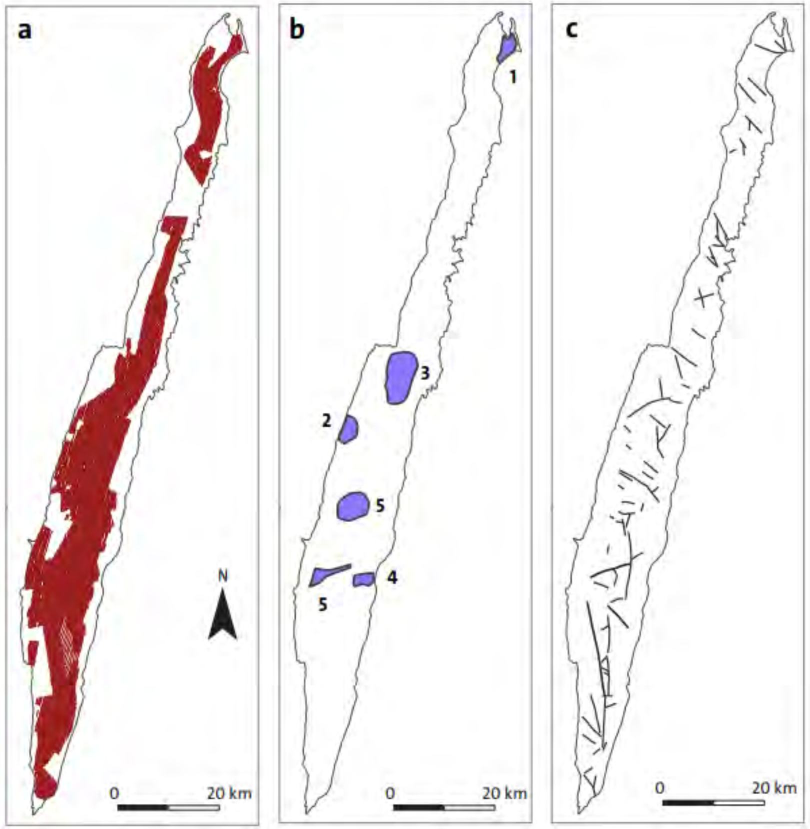


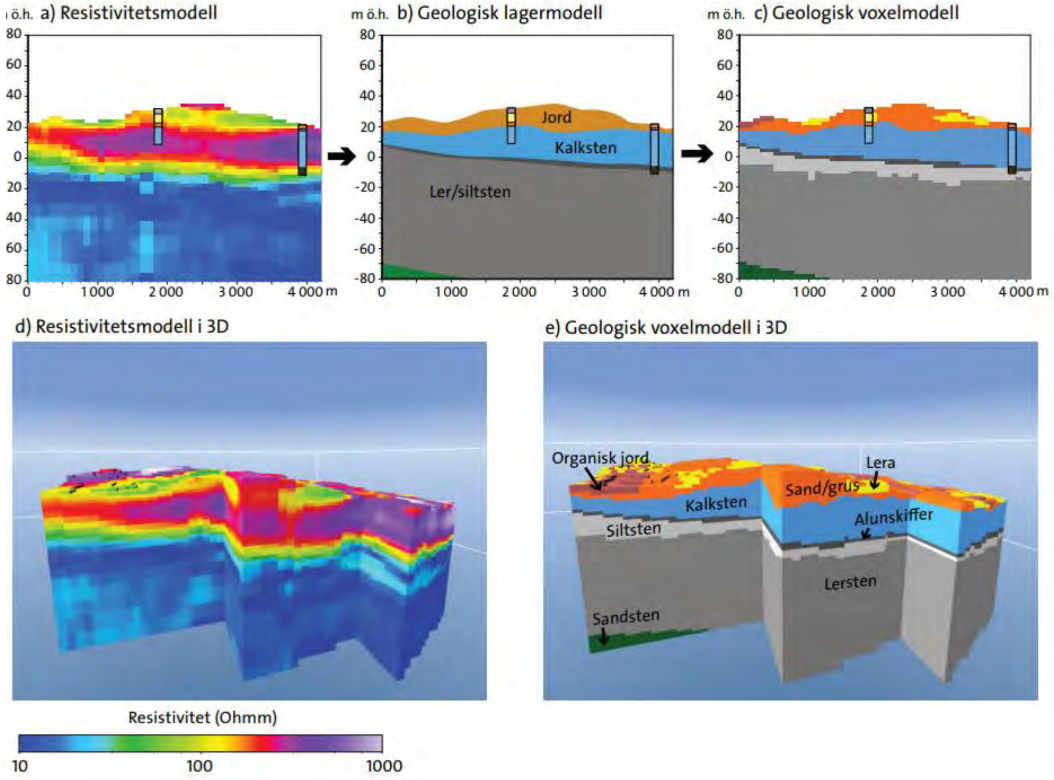



# Groundwater mapping with SkyTEM – Öland 2017

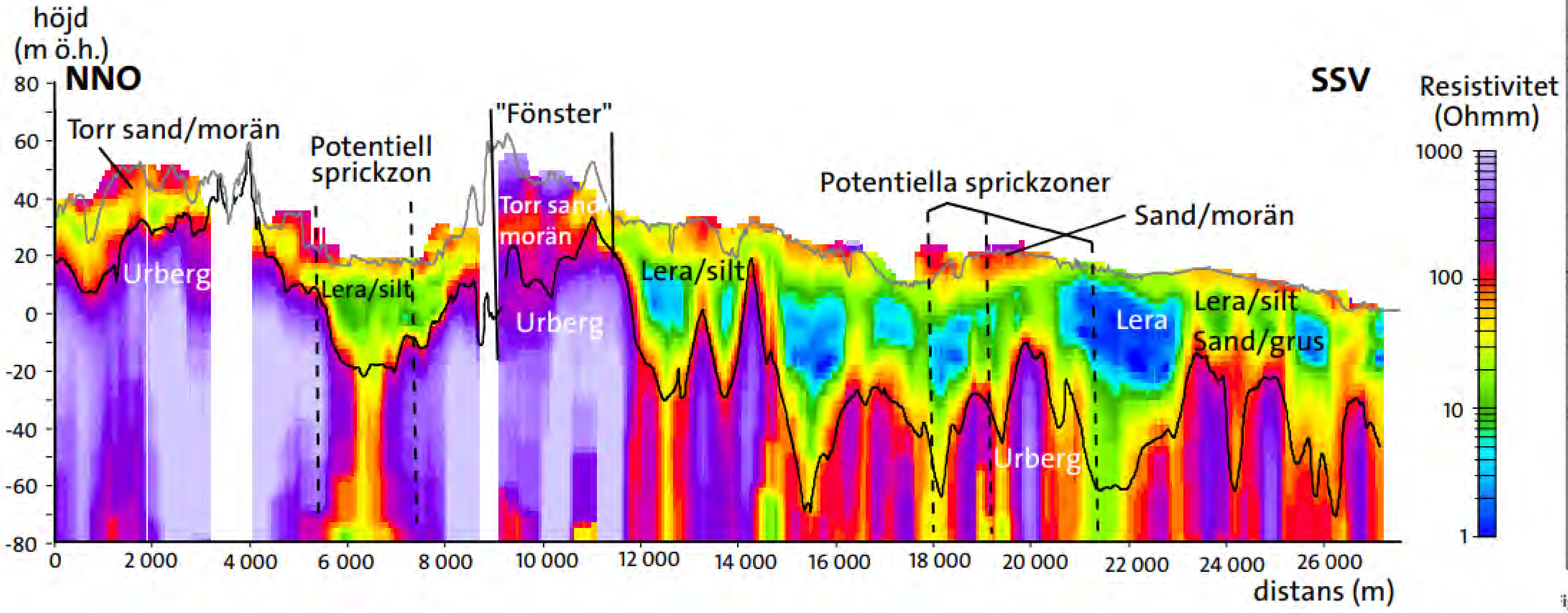


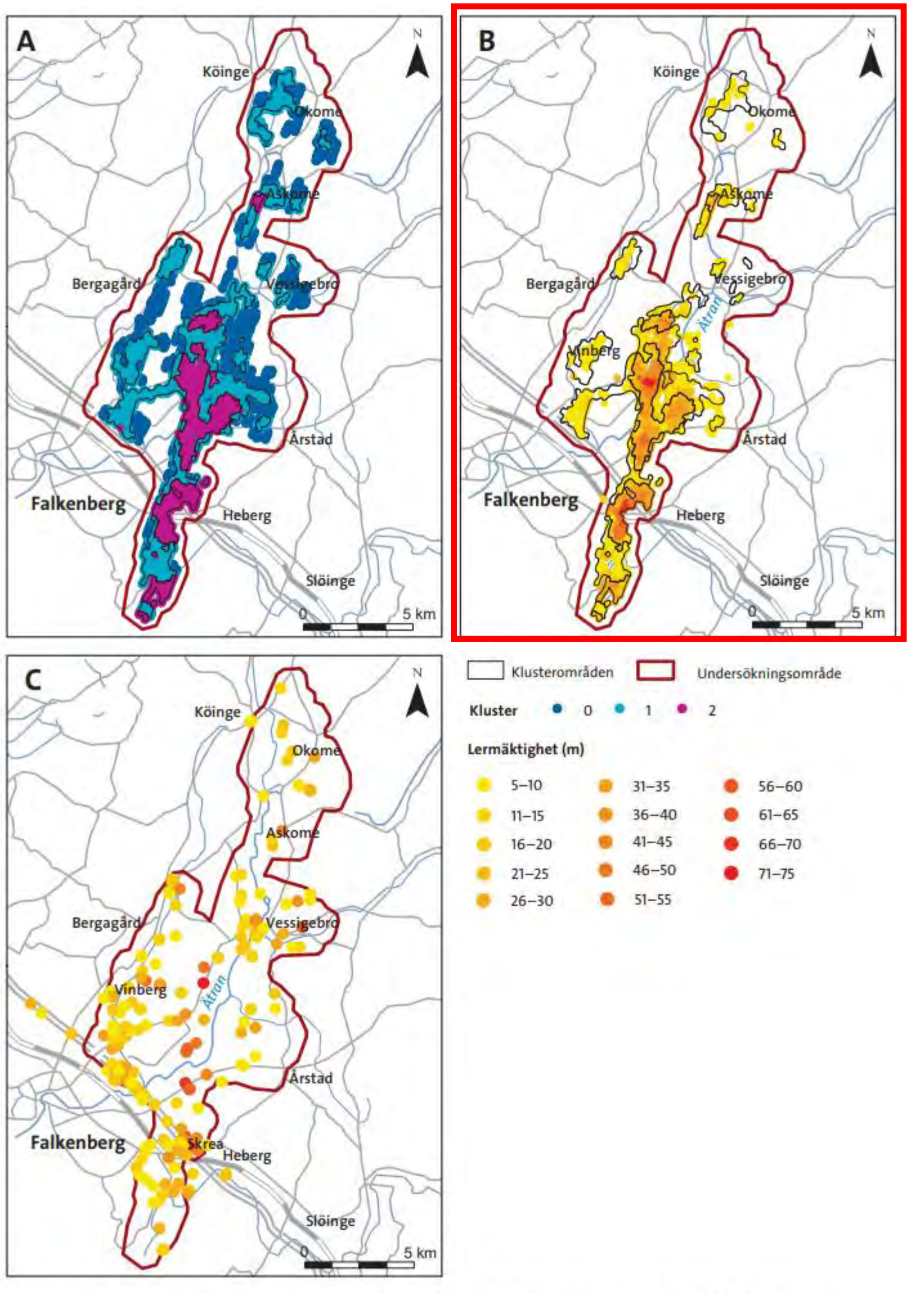



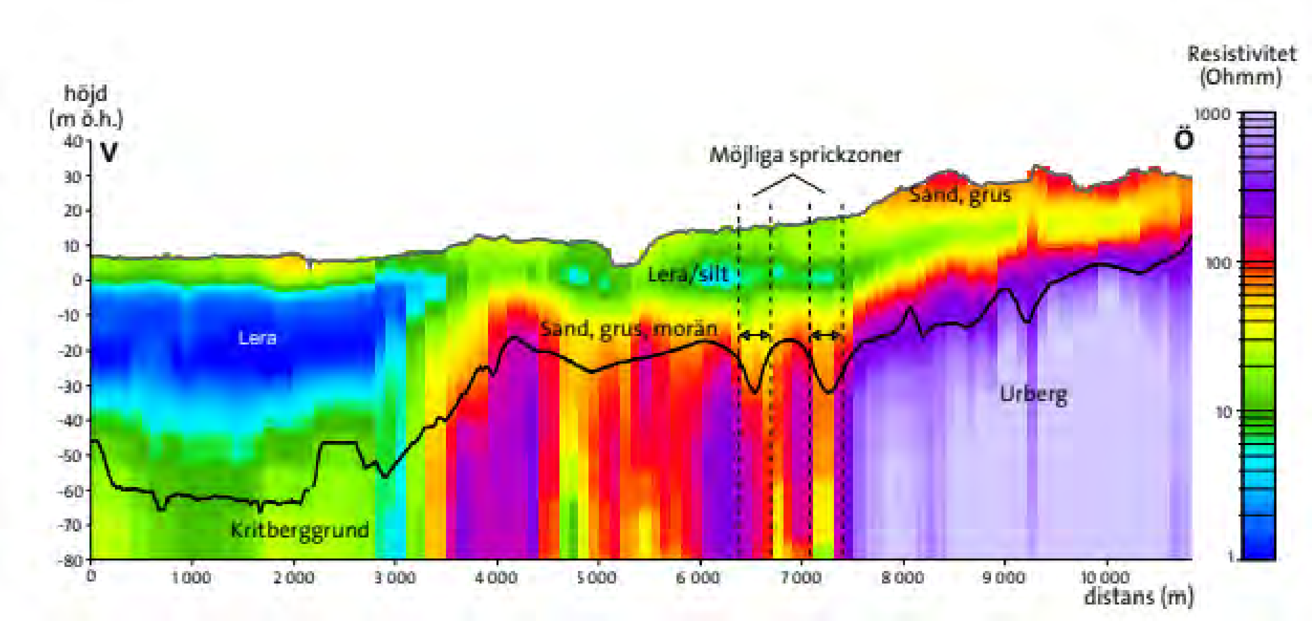
# Groundwater mapping with SkyTEM – Falkenberg

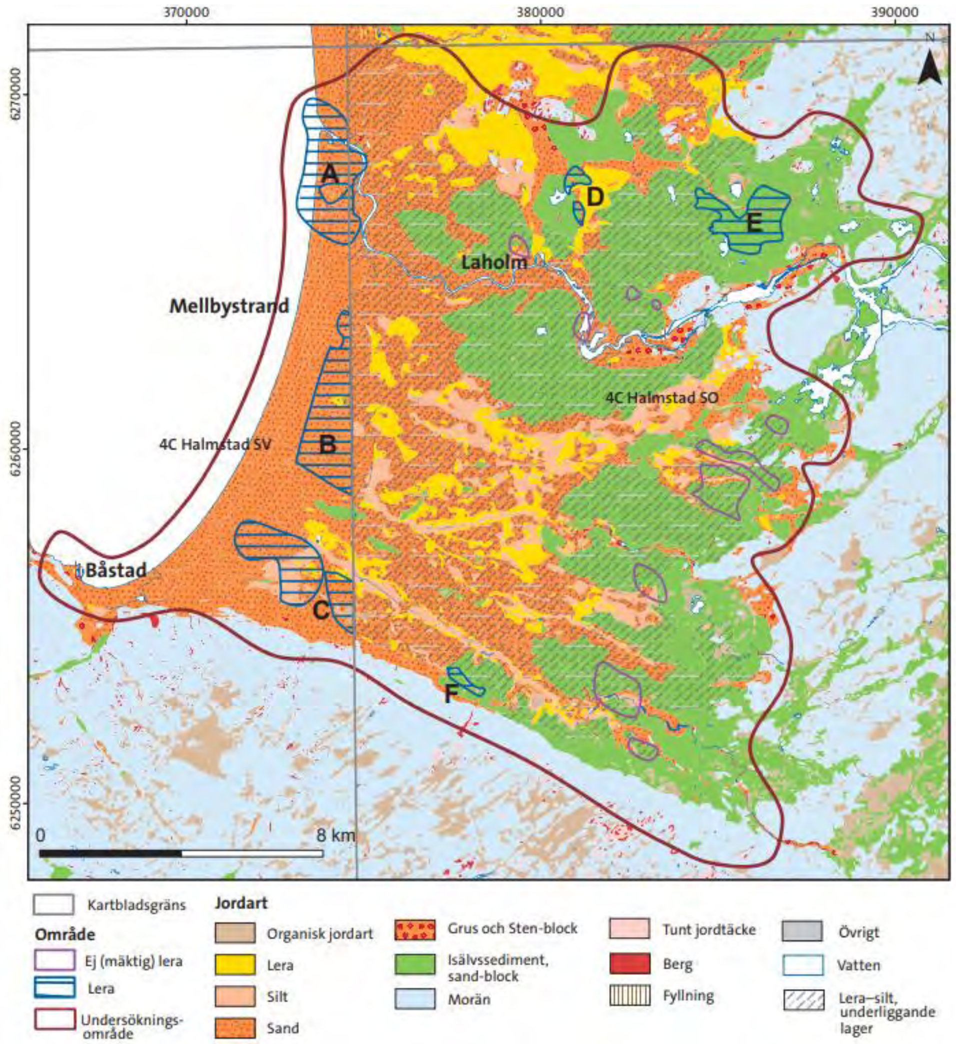



igur 44. A. Resultat från Klusteranalys. B. Lermäktighet från resistivitetsdata. C. Lermäktighet från brunnar.

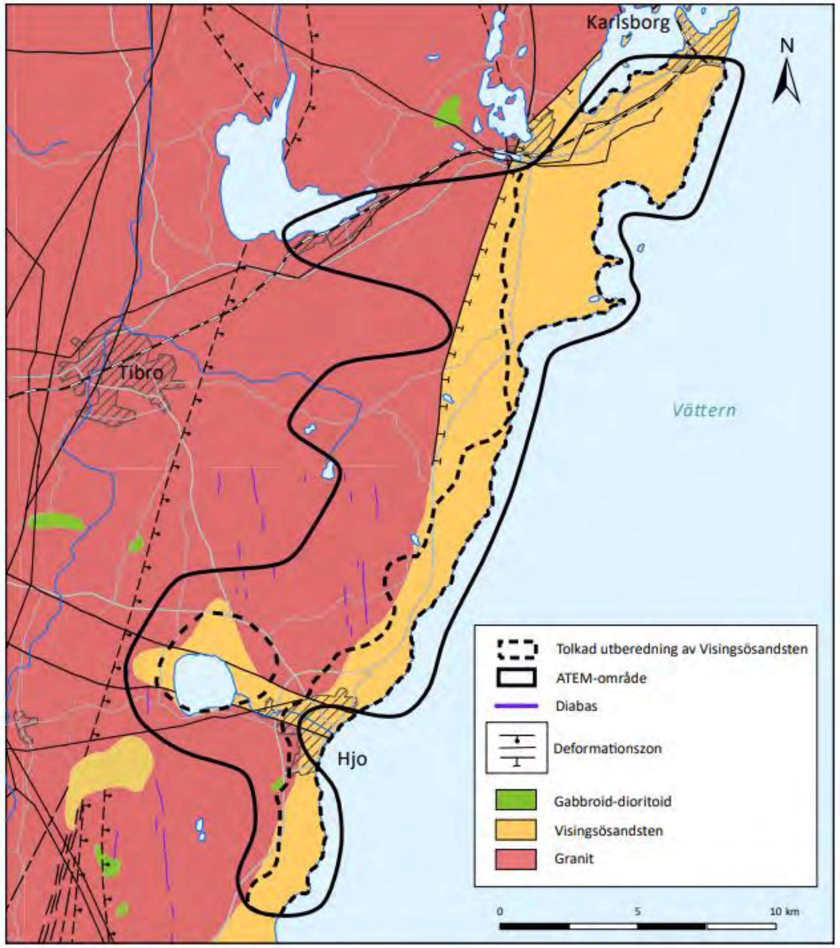
# Groundwater mapping with SkyTEM – Laholm

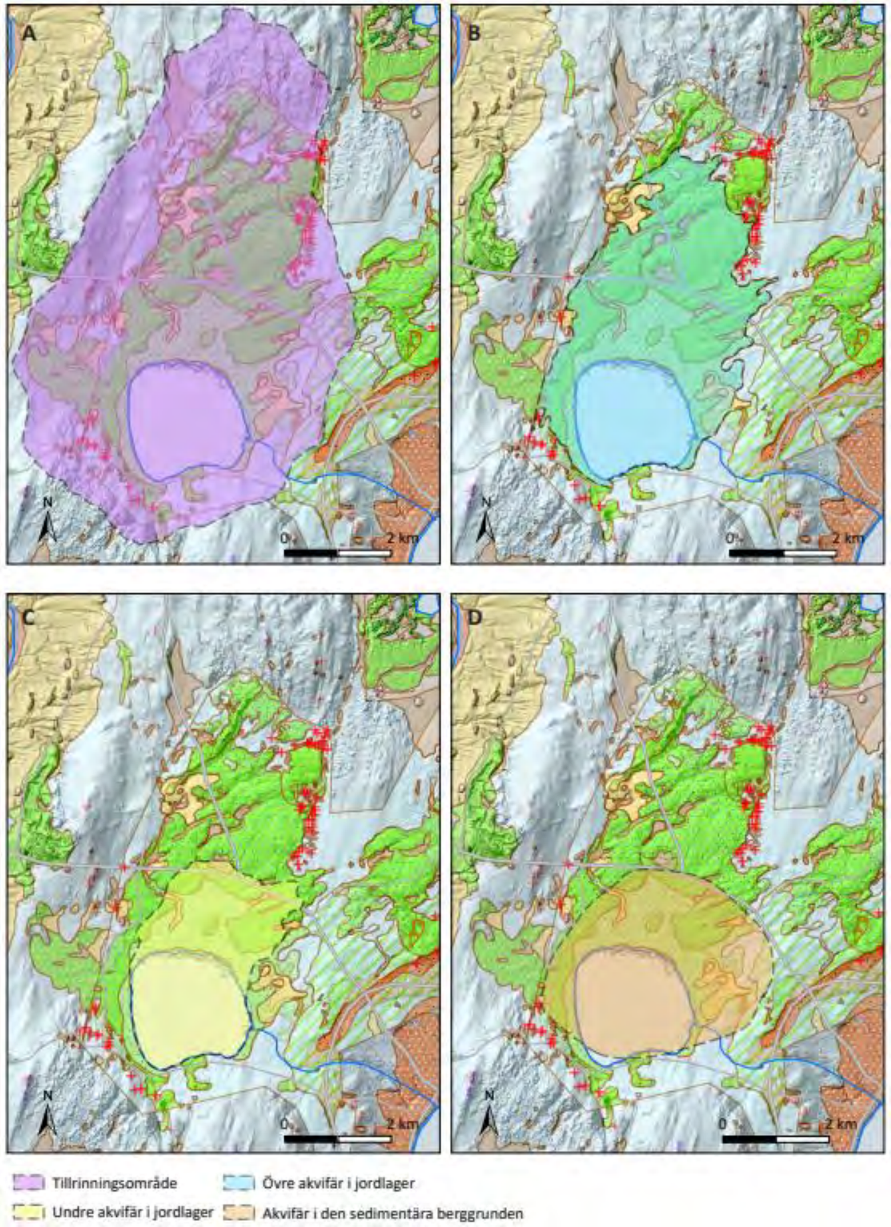



**Figur 22.** Jordartskarta med utpekade områden där denna bör uppdateras efter resultat från ATEM mätningarna. Blåa områden med horisontella blåa streck visar på områden med ler- och siltlager under sand- och grusavlagringar. Lila polygoner visar på område där mäktiga lerlager saknas.

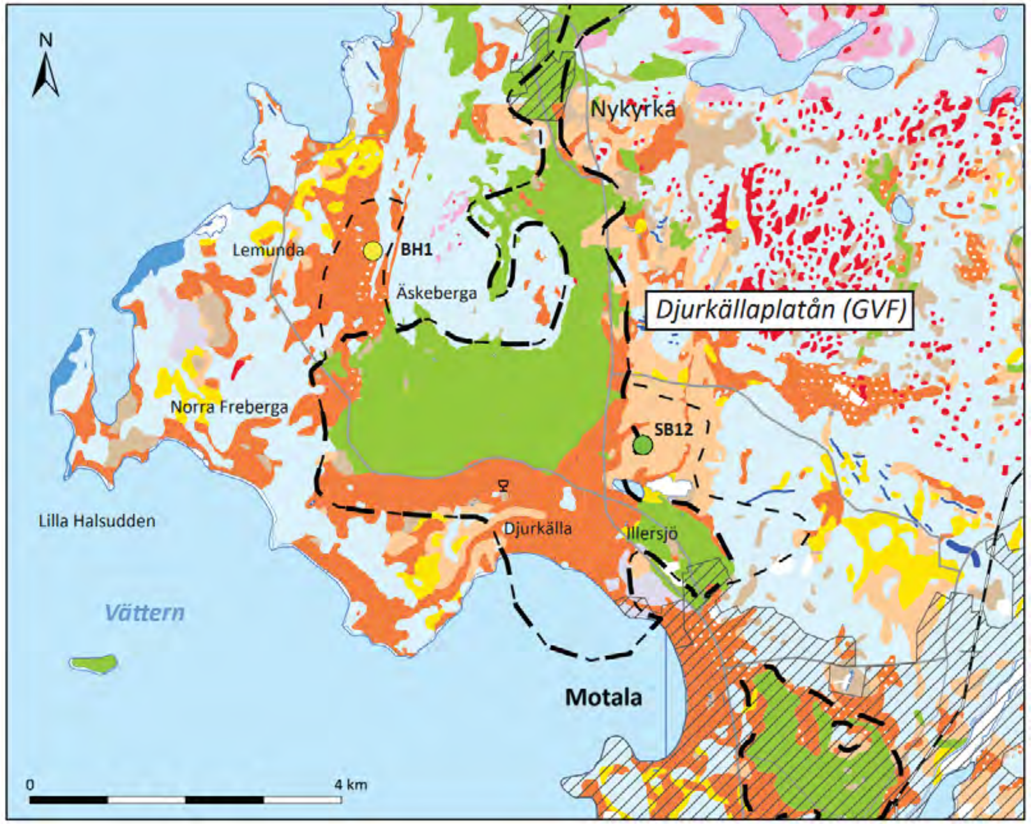
# Groundwater mapping with SkyTEM – Karlsborg/Hjo

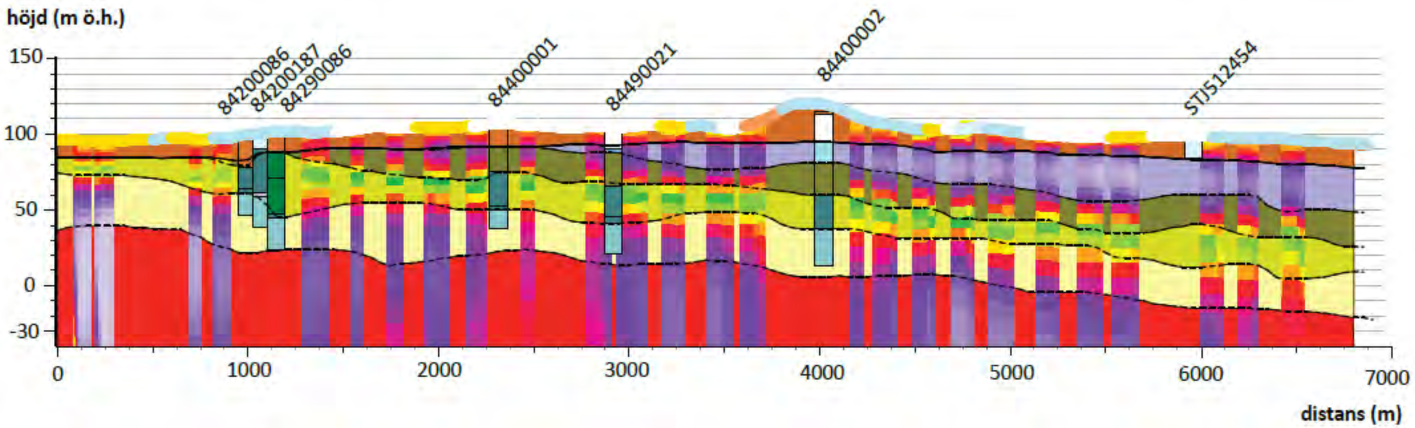




**Figur 28.** Preliminär hydrogeologisk tolkning av tillrinningsområden och akviferer inom området Mullsjön. **A.** Tillrinningsområde. **B.** Övre akvifer i jordlager. **C.** Undre akvifer i jordlager. **D.** Akvifer i Visingsösandstenen.

# Groundwater mapping with SkyTEM – Östergötland

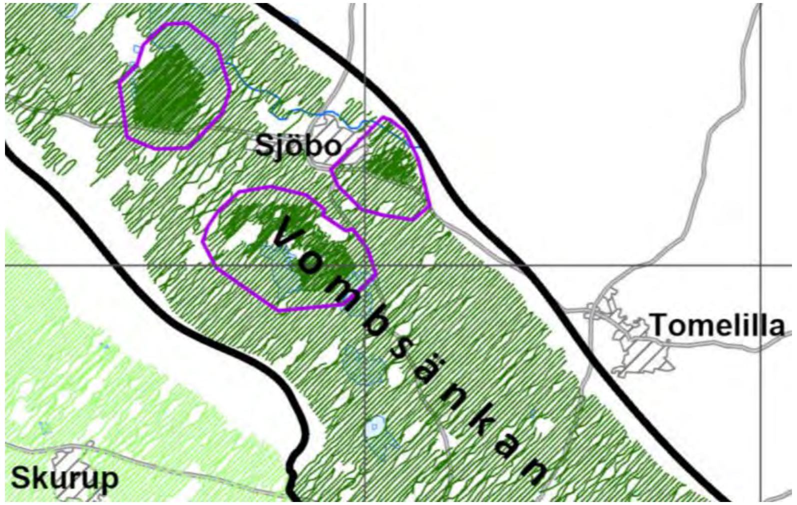



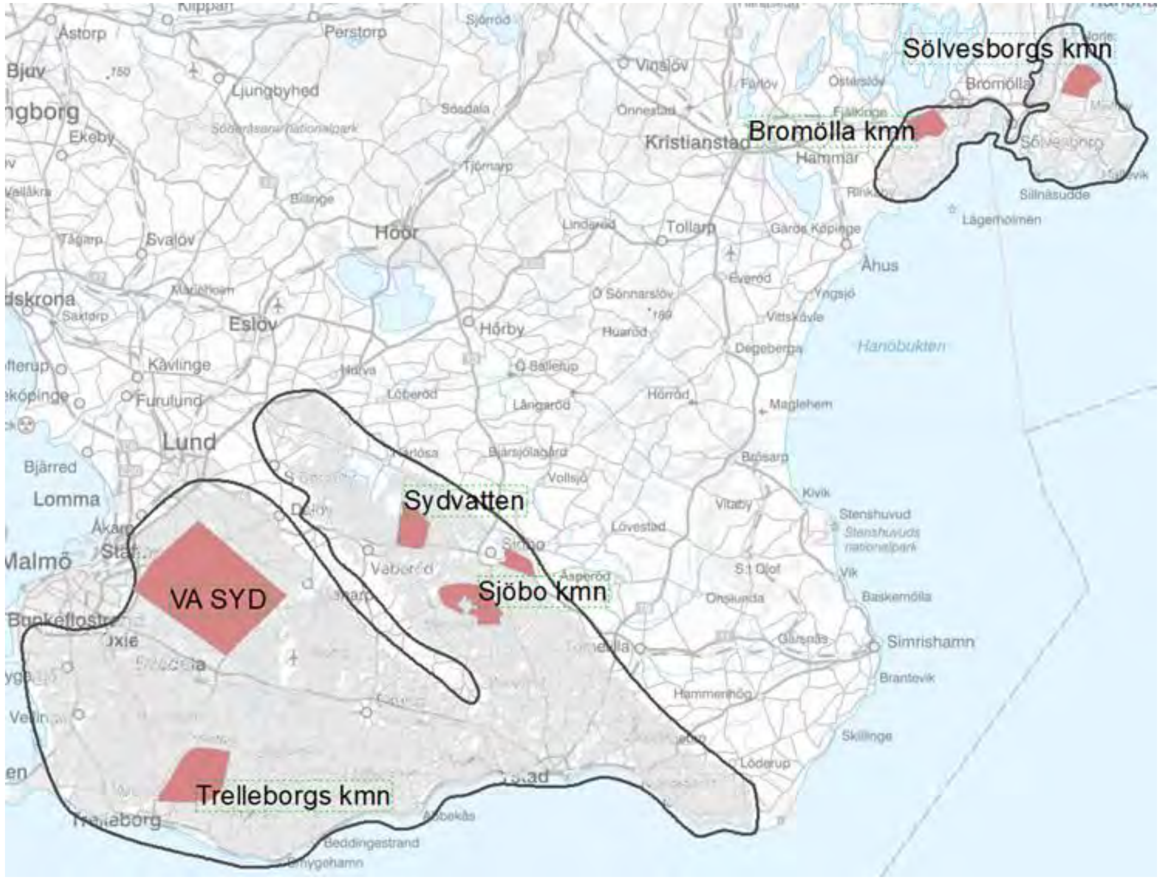
# Groundwater mapping with SkyTEM – Skåne/Blekinge

In 2019, helicopter-borne TEM surveys were carried out over a total of approximately 2,000 km$^2$ in western Blekinge/NW Skåne and SW Skåne.

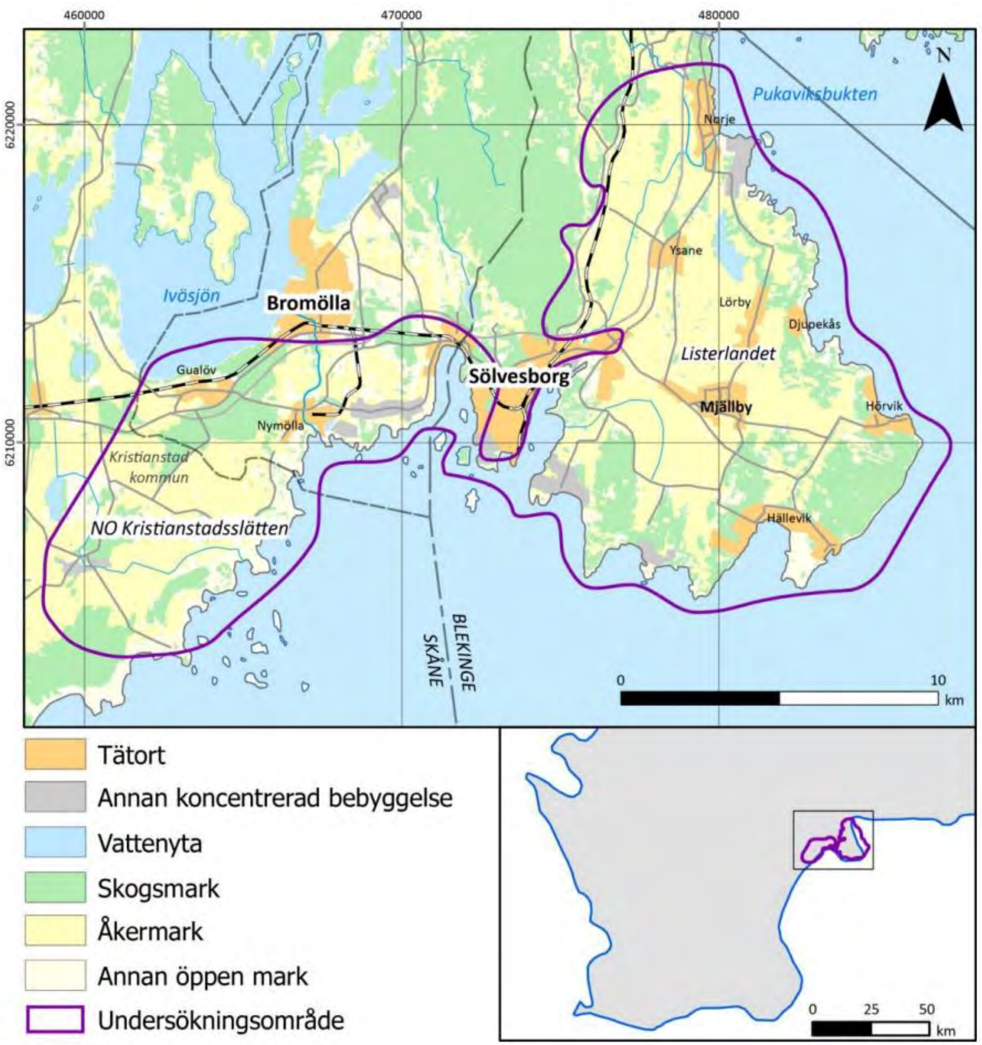
Agreements was made with a number of municipalities in areas of interest for drinking water supply.

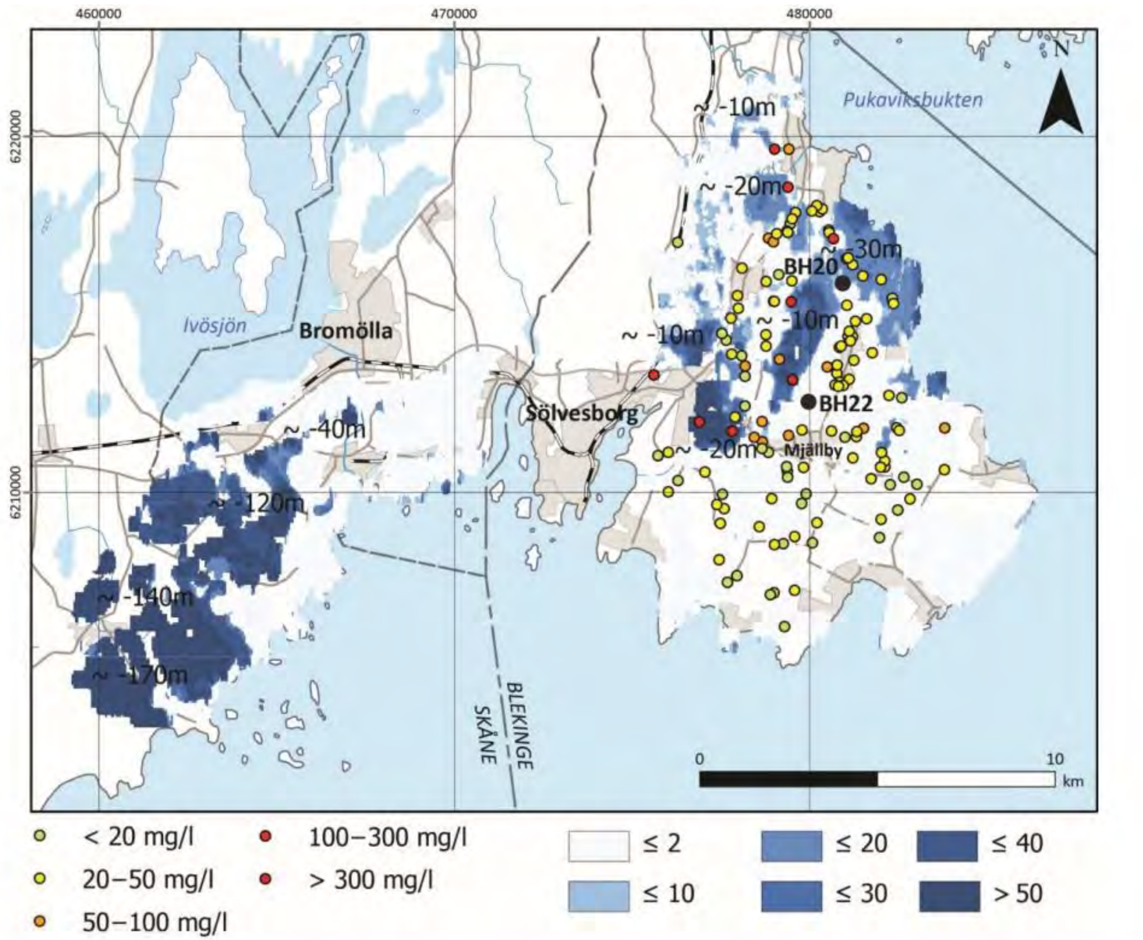
In some areas municipalities got condensed Surveys .



# Groundwatermapping with SkyTEM - Listerlandet

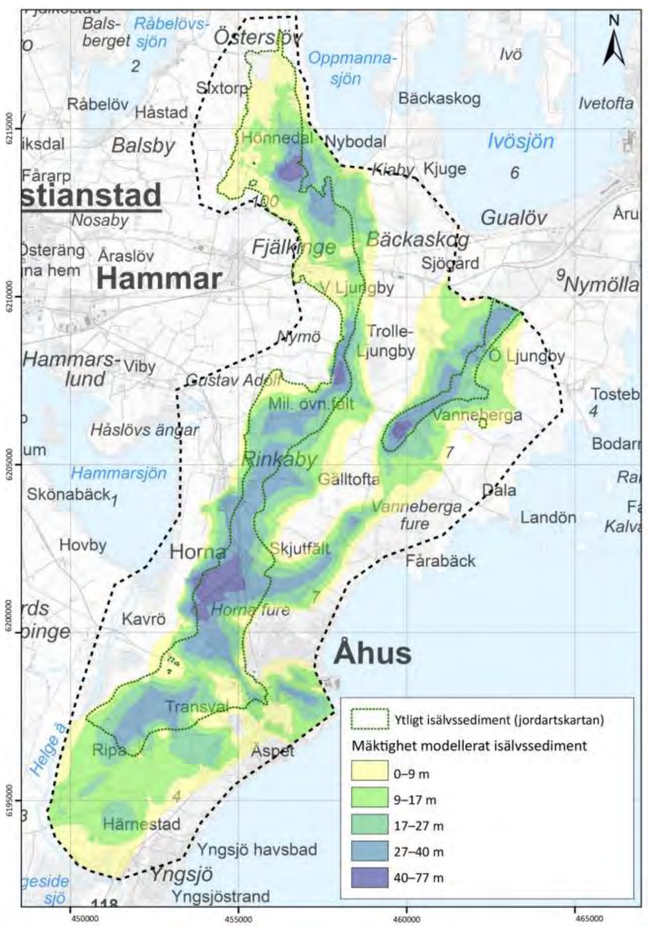


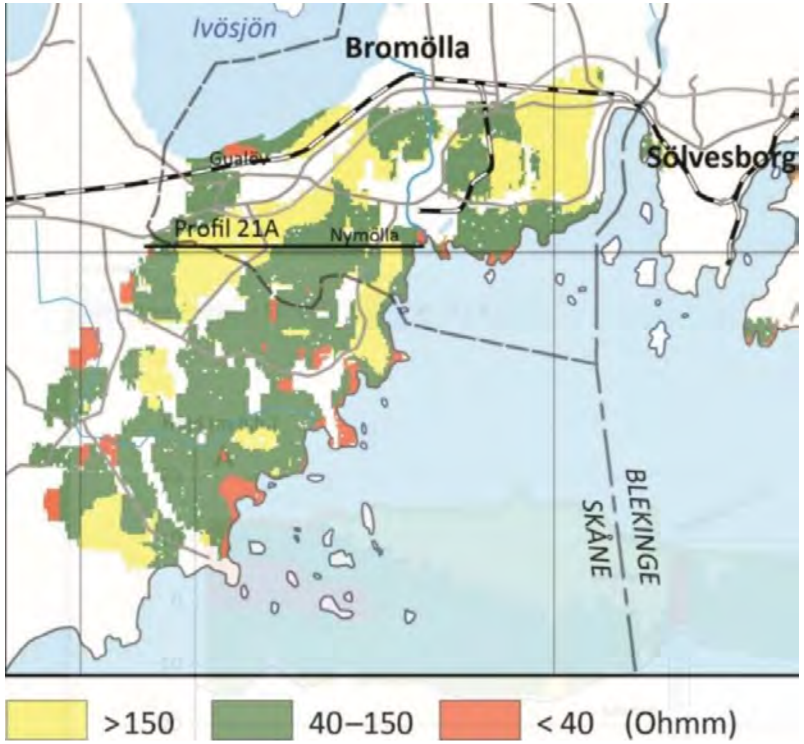



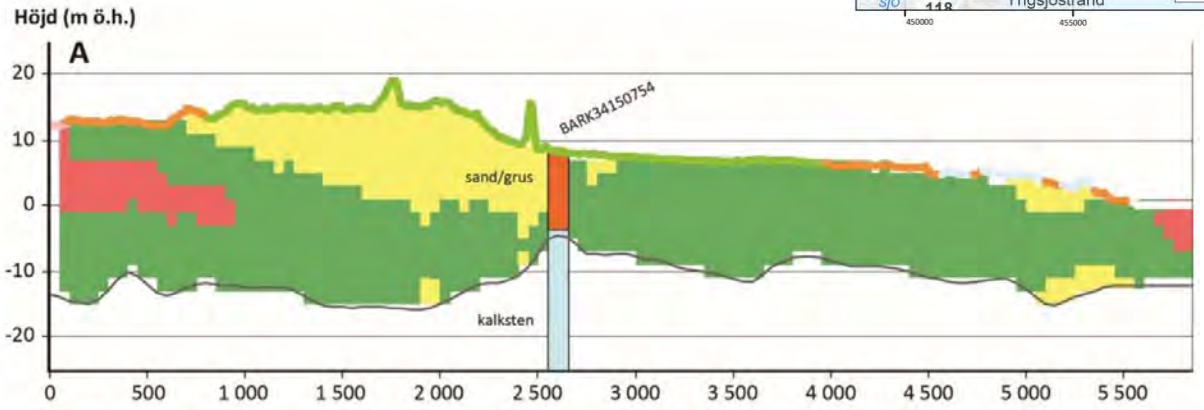

**Figur 36.** Mäktigheten på sedimentärt berg med en resistivitet under 30 Ohmm. Siffrorna visar på ungefärligt djup (RH2000) av överytan för de lågresistiva lagren. Borrningar till detta djup riskerar saltpåverkat grundvatten. Brunnar på Listerlandet visar kloridhalt. Gränserna är satta efter tillståndsklassning i SGUs Bedömningsgrunder (SGU-rapport 2013:01).

# Groundwater mapping with SkyTEM – NW Kristianstad basin

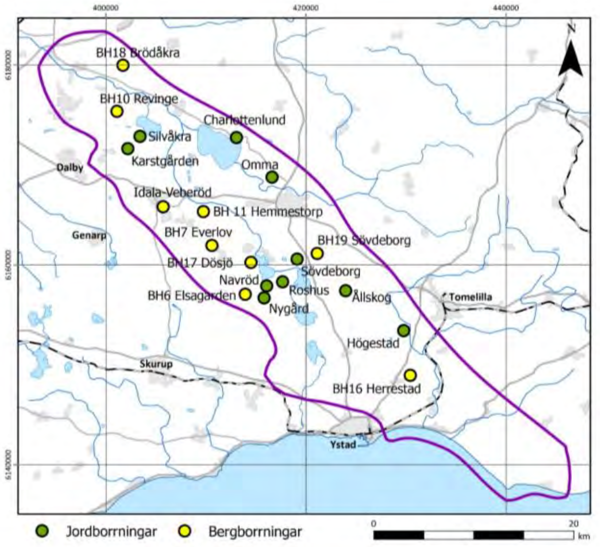
[Hornaåsen, Kristianstadsslätten - geologisk 3D-modell (sgu.se)]

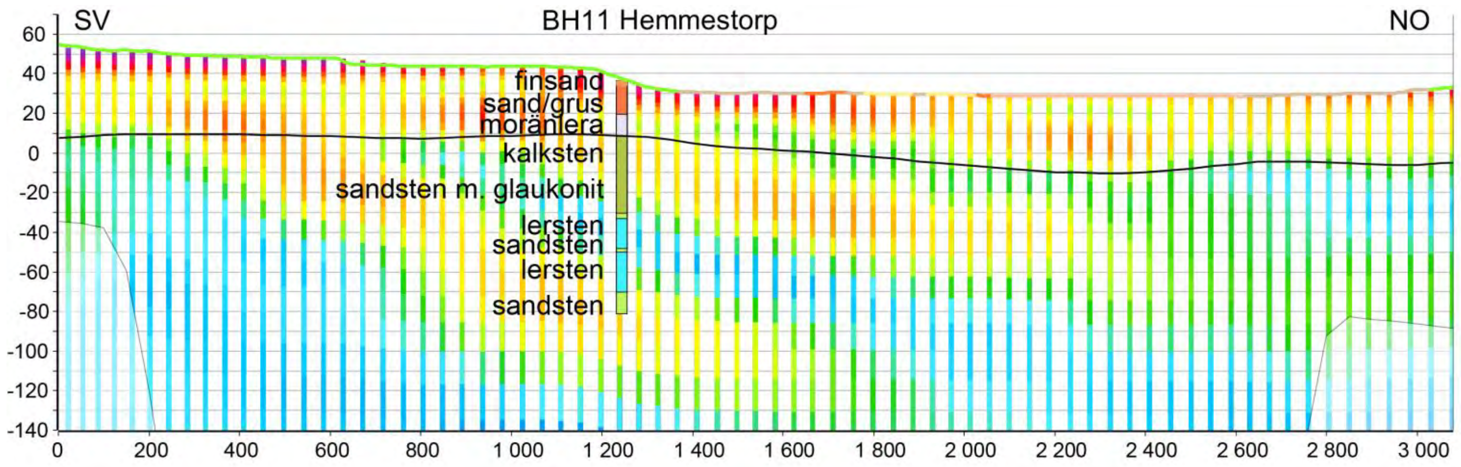


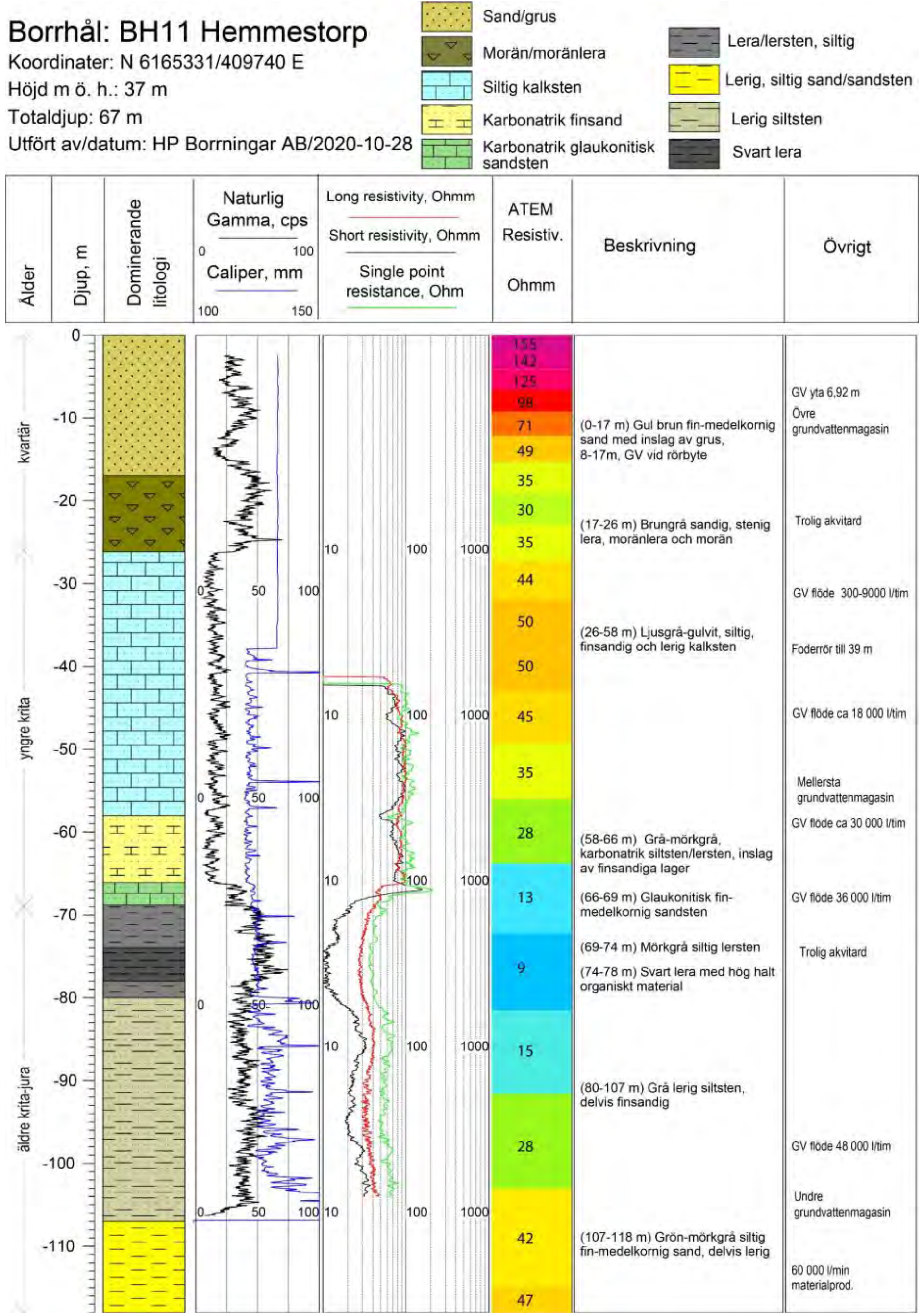



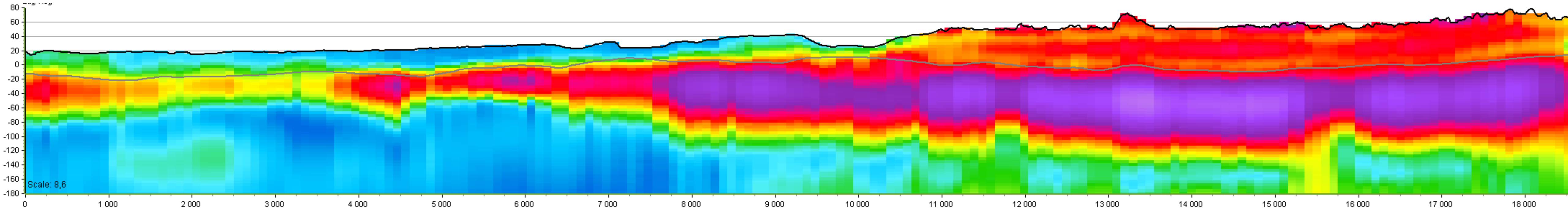
# Groundwater mapping with SkyTEM – Vomb

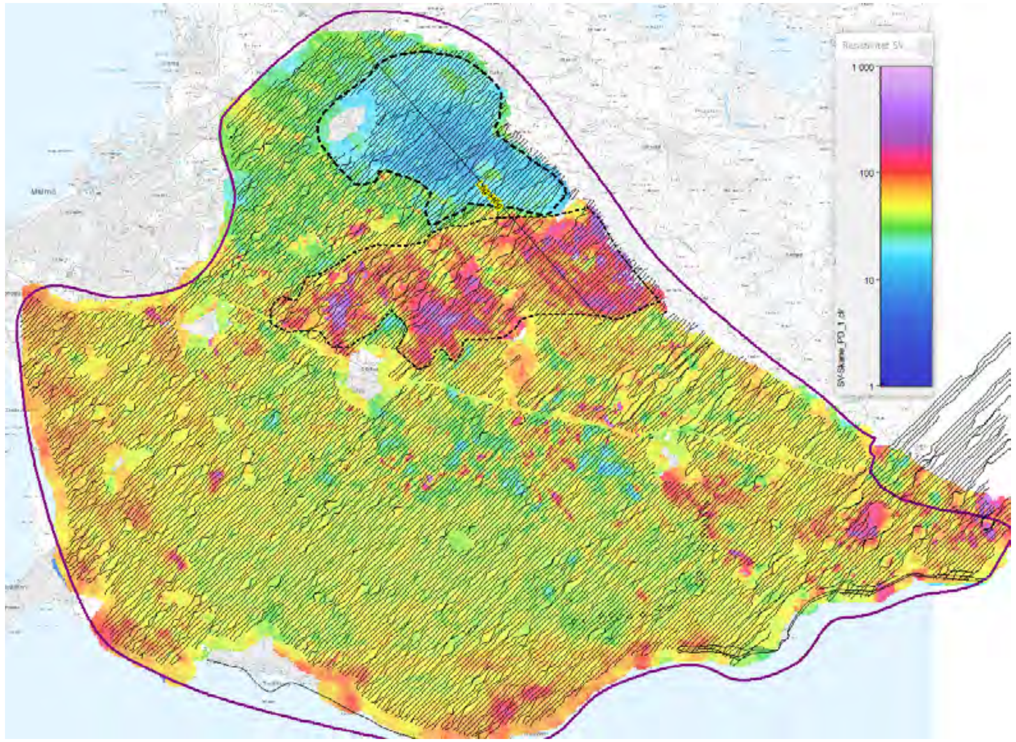


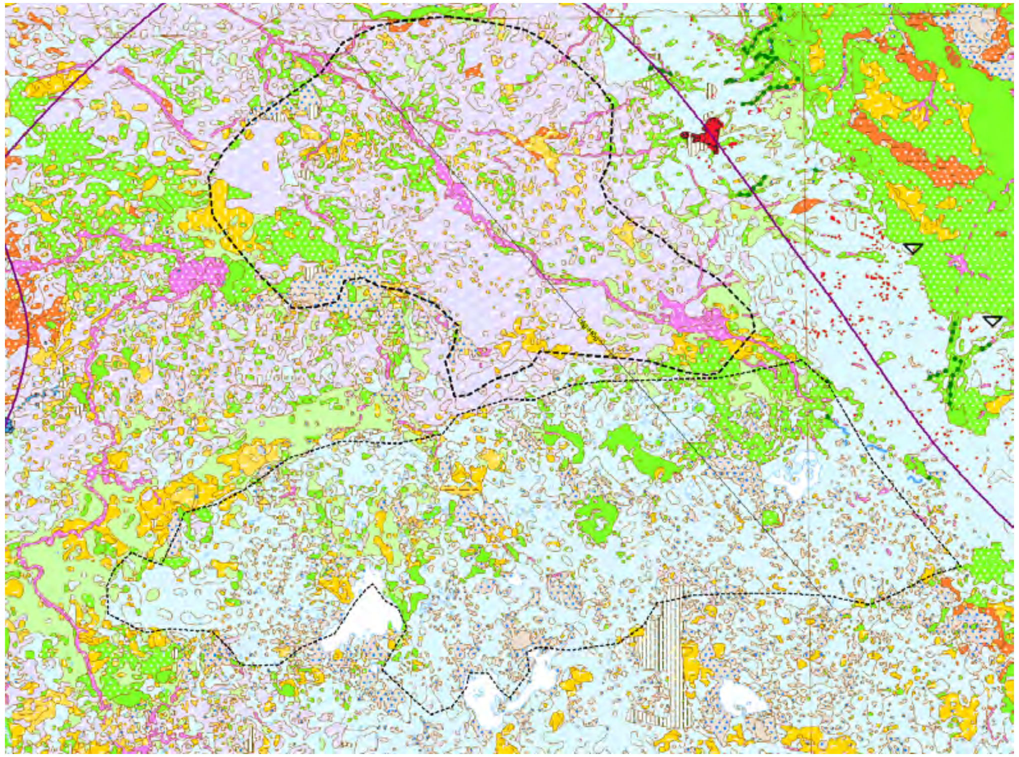



# Groundwater mapping with SkyTEM –SW Scania



# Groundwater mapping with SkyTEM

## Reports

http://resource.sgu.se/produkter/rm/rm136-rapport.pdf

http://resource.sgu.se/produkter/rm/rm140-rapport.pdf

https://resource.sgu.se/produkter/rm/rm145-rapport.pdf

http://resource.sgu.se/produkter/rm/rm147-rapport.pdf

http://resource.sgu.se/produkter/sgurapp/s2024-rapport.pdf

https://resource.sgu.se/dokument/publikation/sgurapport/sgurapport202033rapport/s2033-rapport.pdf

https://resource.sgu.se/dokument/publikation/sgurapport/sgurapport202041rapport/s2041-rapport.pdf

https://resource.sgu.se/dokument/publikation/sgurapport/sgurapport202123rapport/s2123-rapport.pdf

https://resource.sgu.se/dokument/publikation/sgurapport/sgurapport202130rapport/s2130-rapport.pdf

## 3D-models, resistivity sections/maps

https://apps.sgu.se/sgu3d/

# Comparison of hydrogeological properties based on DCIP, (surface) NMR and hydraulic tests

TINA MARTIN ET AL.

2023-11-14

Et al: T. Dahlin, A. Mendoza, A. Kass, D. Grombacher, C. Butron,
With contributions from: U. Werban, S. Landmark, S. Costabel, M. Müller-Petke, T. Günther, A. Weller, M. Schmutz, field crew LU, AU, Niras, ENSEGID….

# Motivation

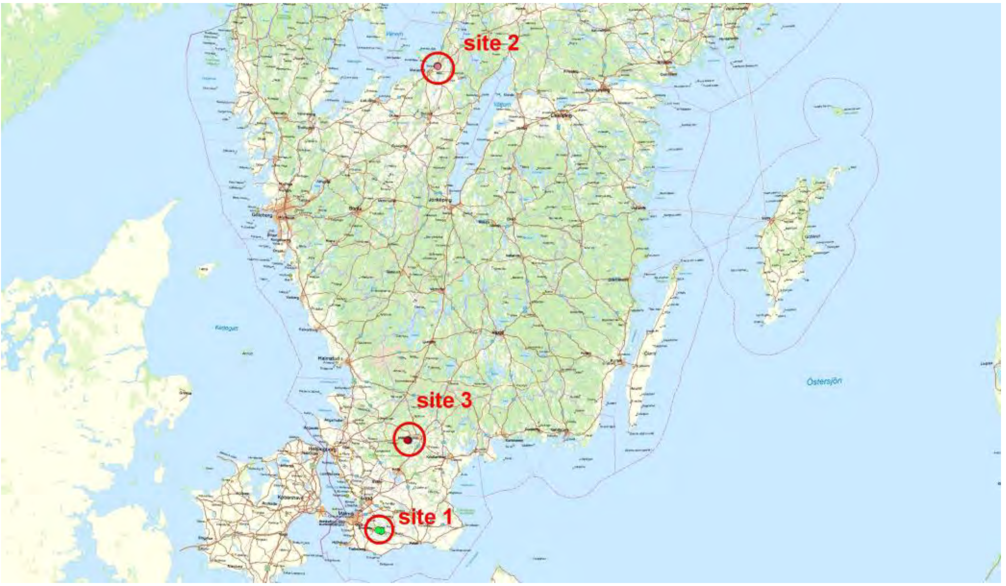
- Crucial to know for a variation of applications: groundwater areas, infrastructure projects, agriculture, etc.
- **Can we get hydrogeological information from geophysical data?**

# Research project

- Nov. 2020 – Dec 2022, funded by Trafikverket
- Develop a reliable and time & cost-efficient methodology for spatially mapping of the groundwater conditions
- **Combining DCIP + SNMR** to determine/estimate **hydrological properties** of the underground
- **Evaluation** of the methods regarding **hydrological information value**, as well as **robustness** in measurement environments with different signal interference conditions

**Test site criterias:**

- Interesting (hydro-) geology
- Noise level
- Accessible
- Related to infrastructure projects

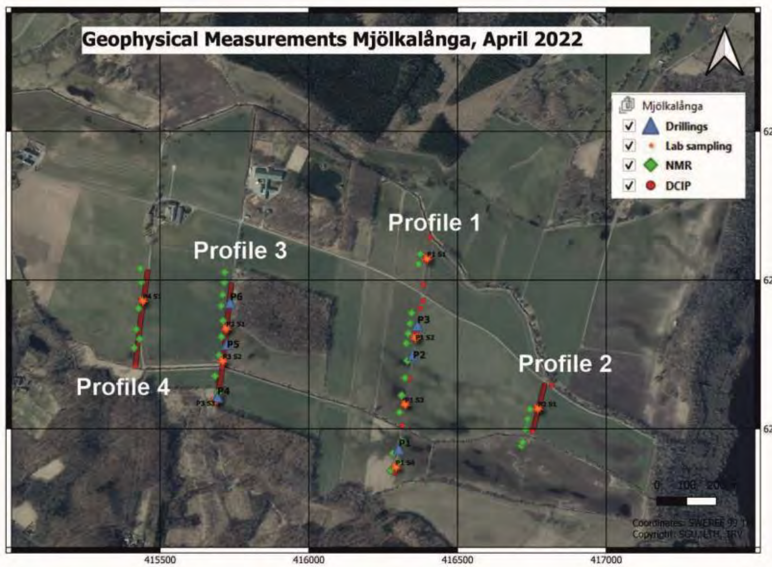


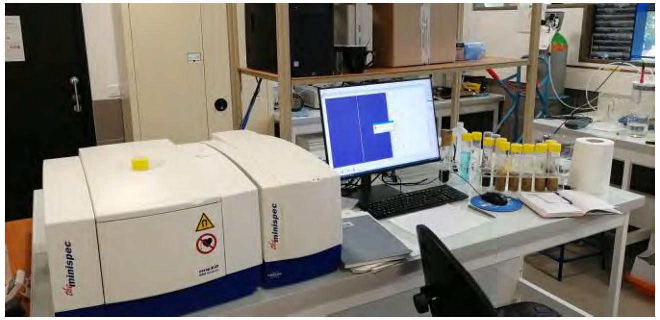

**Measurements:**

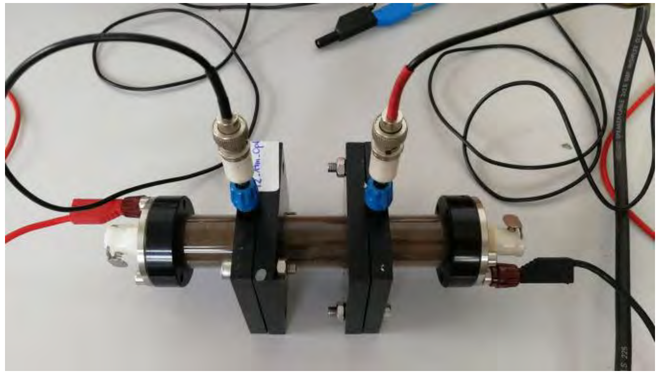
Site 1: E65 - Svedala (May 2021),
Site 2: E20 - Mariestad (Oct. 2021),
Site 3: In the middle of nowhere - Mjölkalånga (April 2022)

TRAFIKVERKET
SWEDISH TRANSPORT ADMINISTRATION

# Test site Mjölkalånga & methods



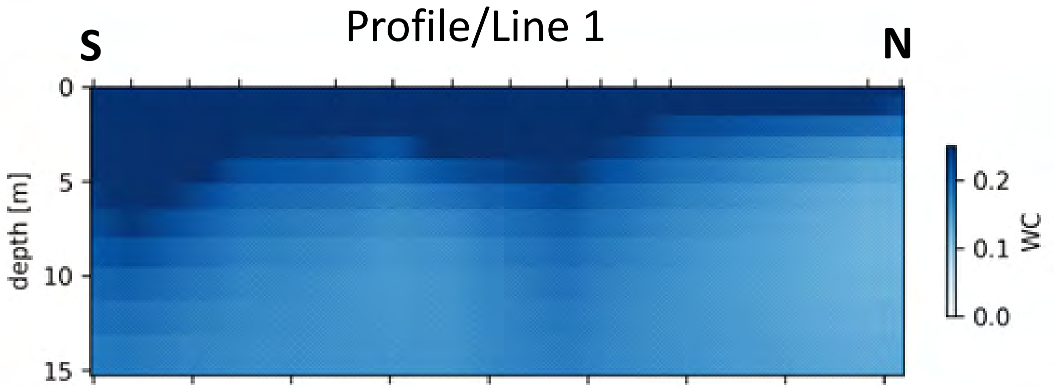





- Test site in Sweden, sandy-clay
- 4 DCIP profiles, 33 SNMR soundings
- 6 HPT drillings and slug tests
- Lab samples (K-Sat, SIP, NMR)

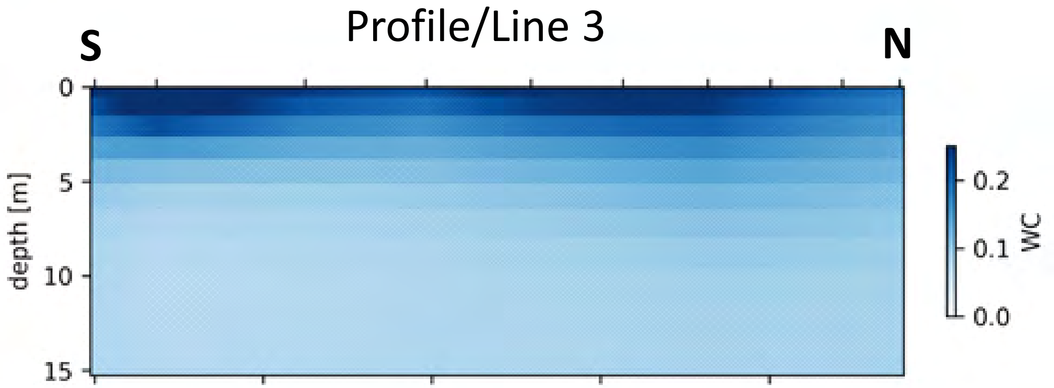
# Surface NMR


N
Line 1
Line 4
Line 6
Line 3
Line 5
Line 2
S
WGS84 UTM Zone 33N
415500
416000
416500
6223000
6222500


Profile/Line 1
S
N
depth [m]
0
5
10
15
WC
0.2
0.1
0.0

# Surface NMR

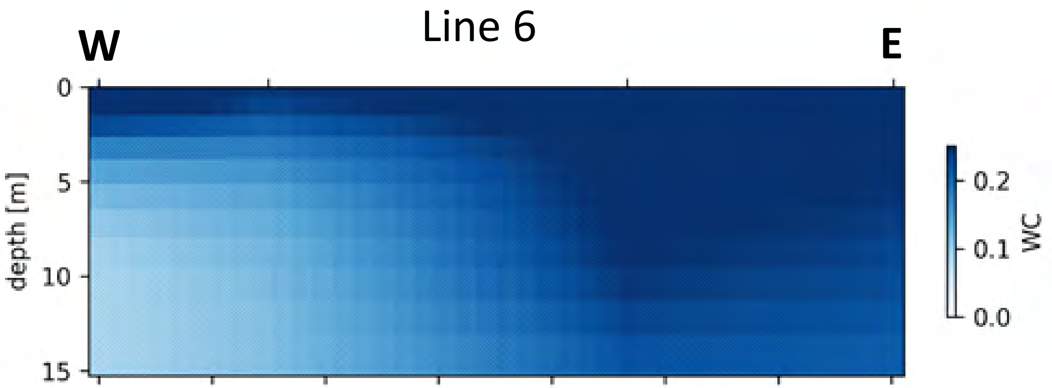
N
S
Line 1
Line 2
Line 3
Line 4
Line 5
Line 6
WGS84 UTM Zone 33N
415500
416000
416500

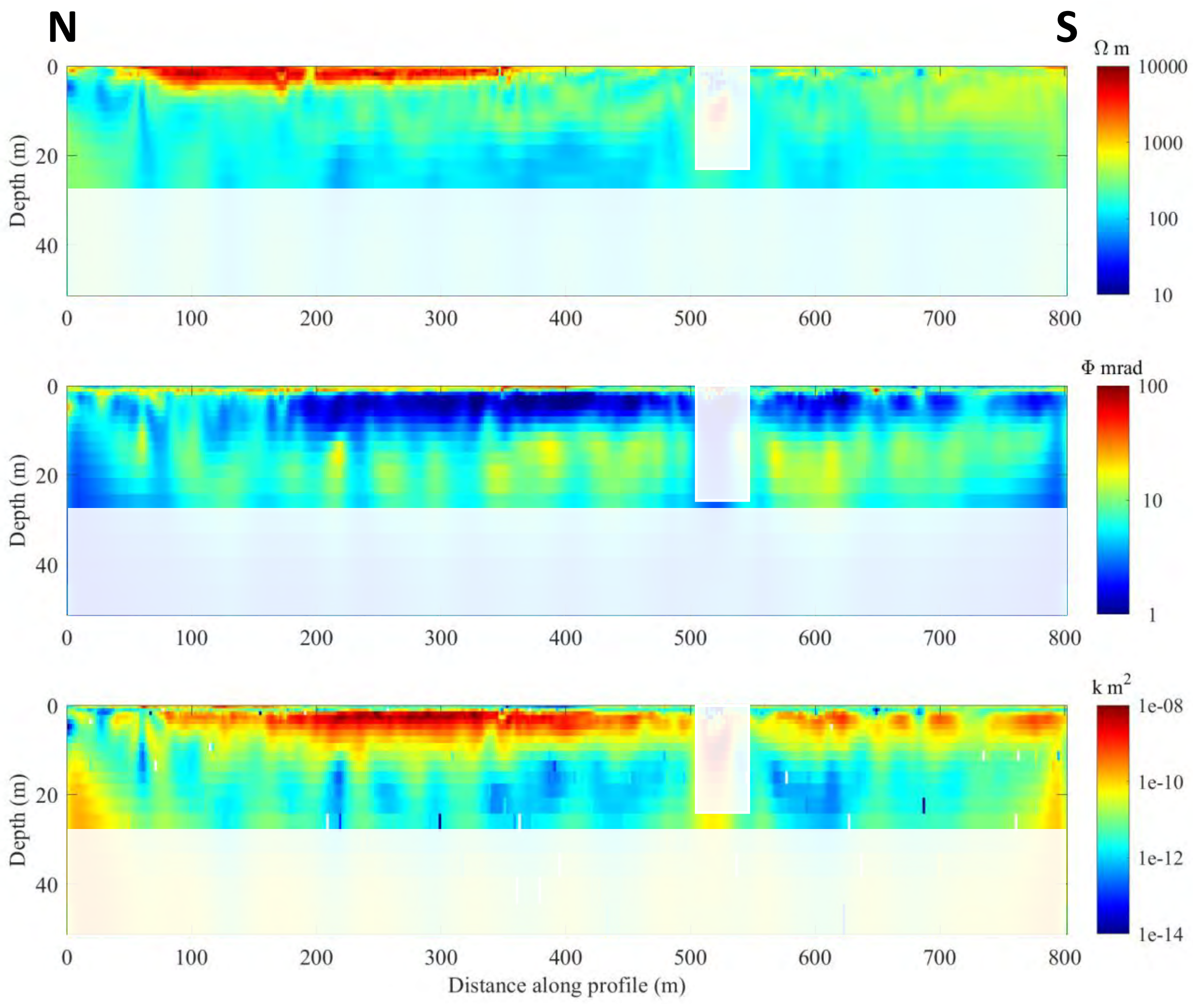
Profile/Line 3
S
N
depth [m]
0
5
10
15
WC
0.2
0.1
0.0

# Surface NMR


W
Line 6
Line 4
Line 3
Line 1
Line 5
Line 2
E
WGS84 UTM Zone 33N
415500
416000
416500
6222500
6223000

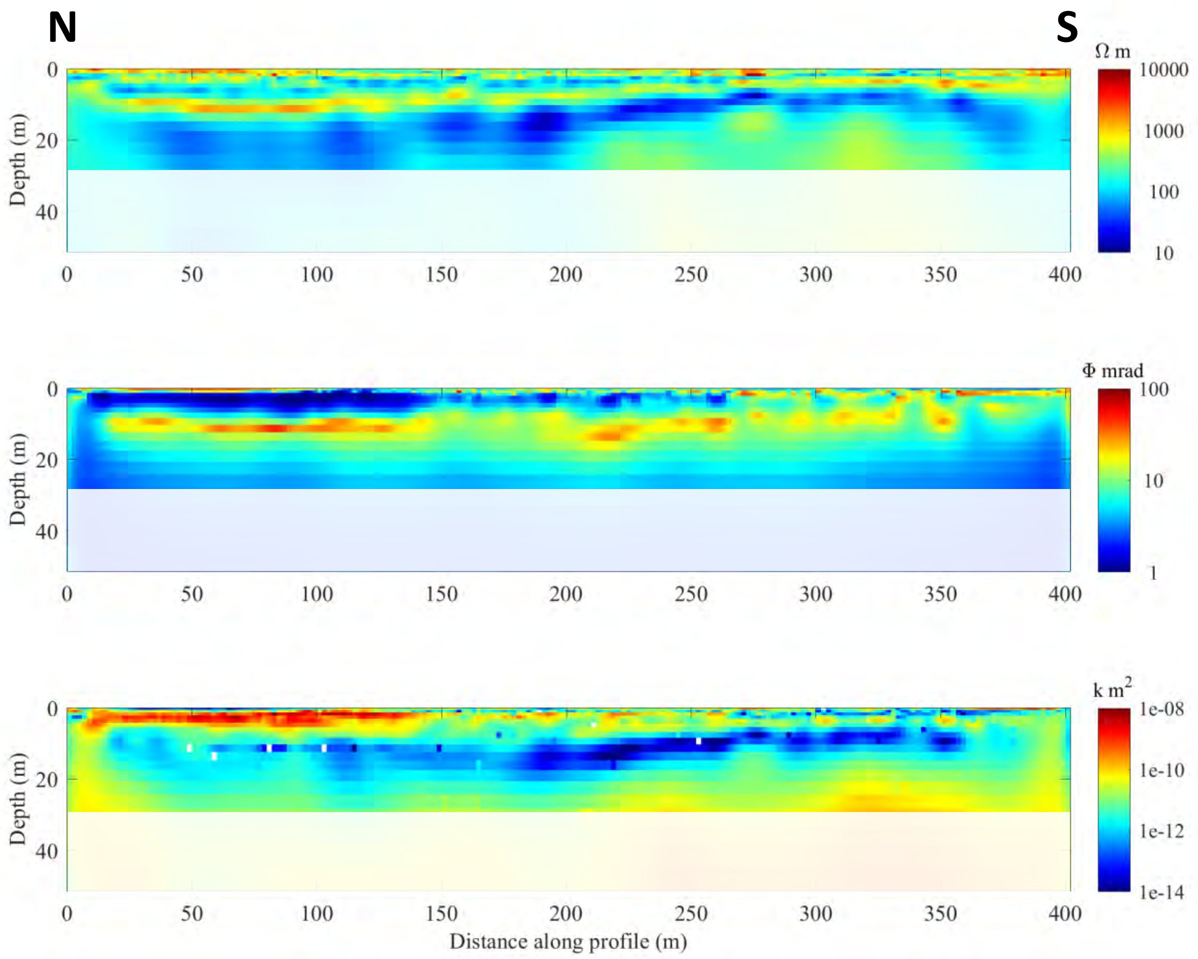

Line 6
W
E
depth [m]
0
5
10
15
WC
0.2
0.1
0.0

# DCIP – profile 1



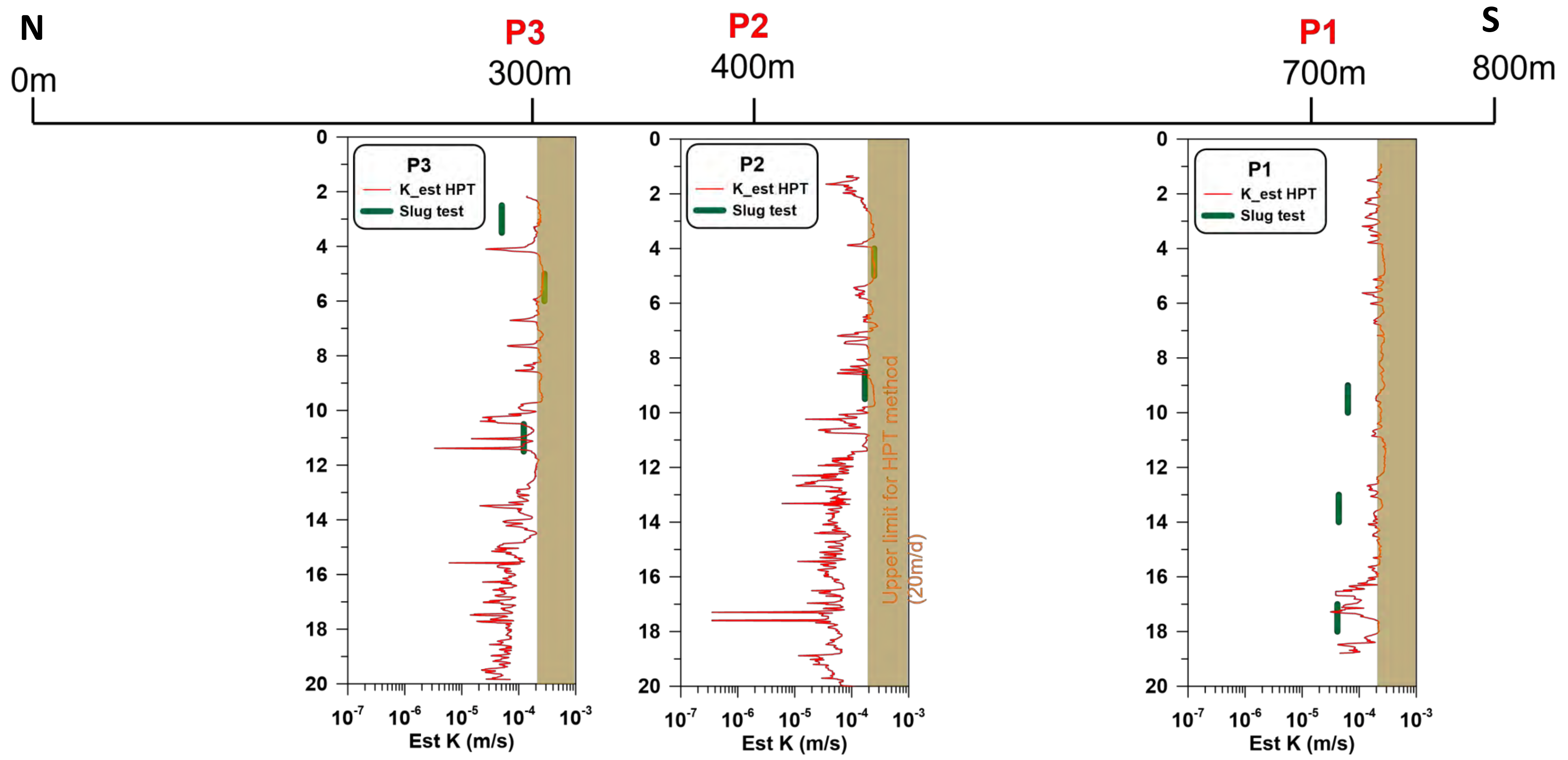

AarhusInv

# DCIP – profile 3

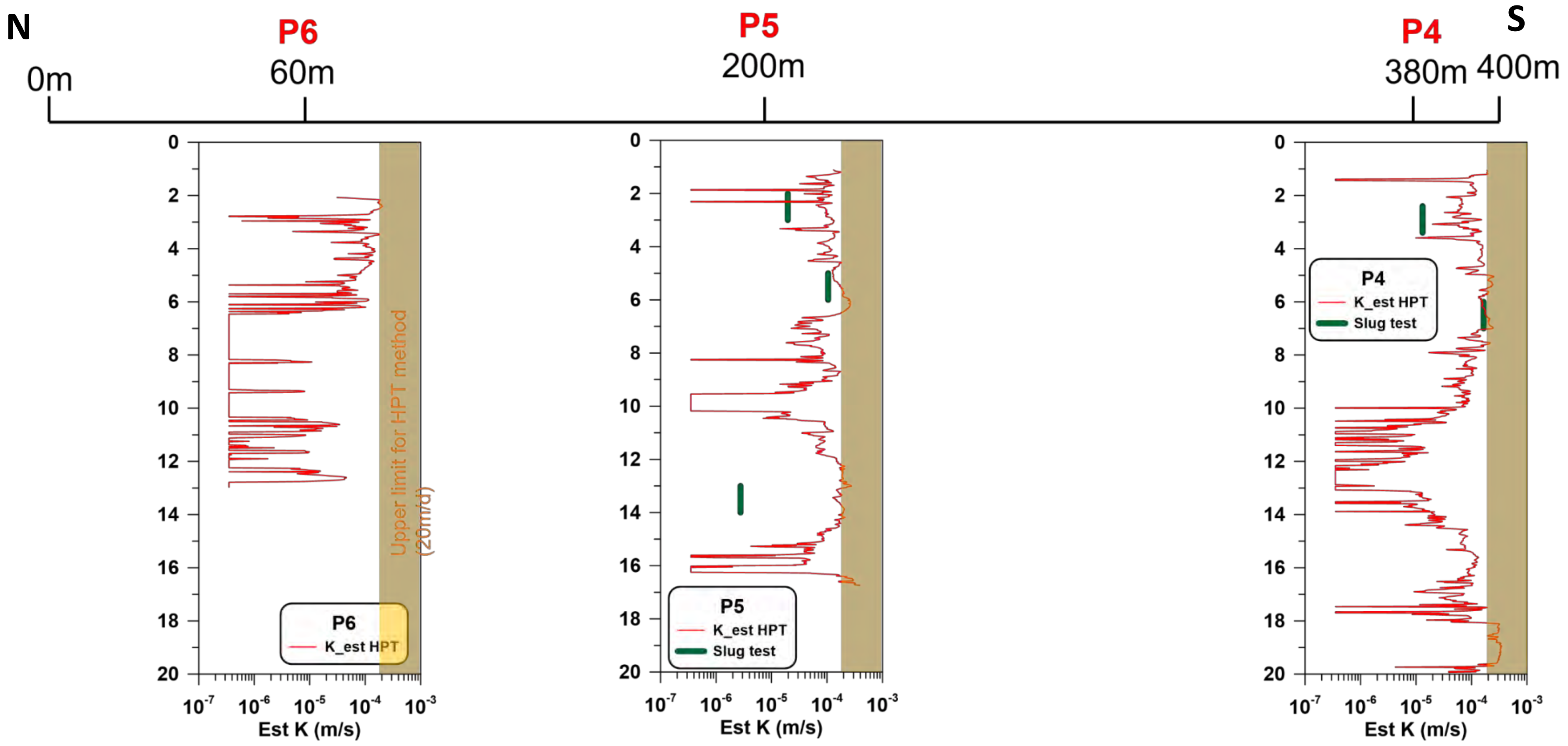



AarhusInv

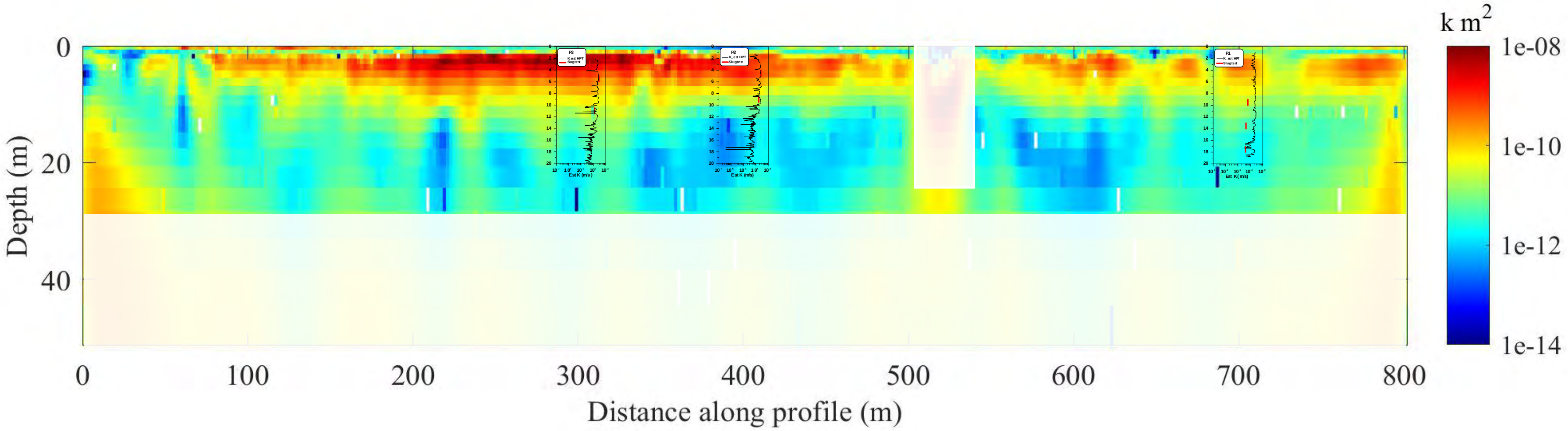
# HPT and slug tests - profile 1

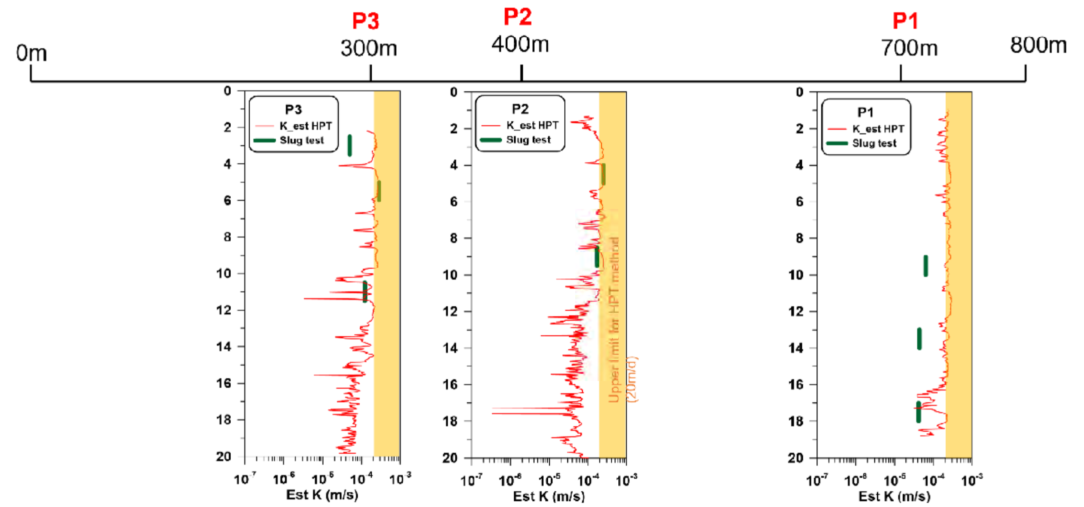


# HPT and slug tests - profile 3

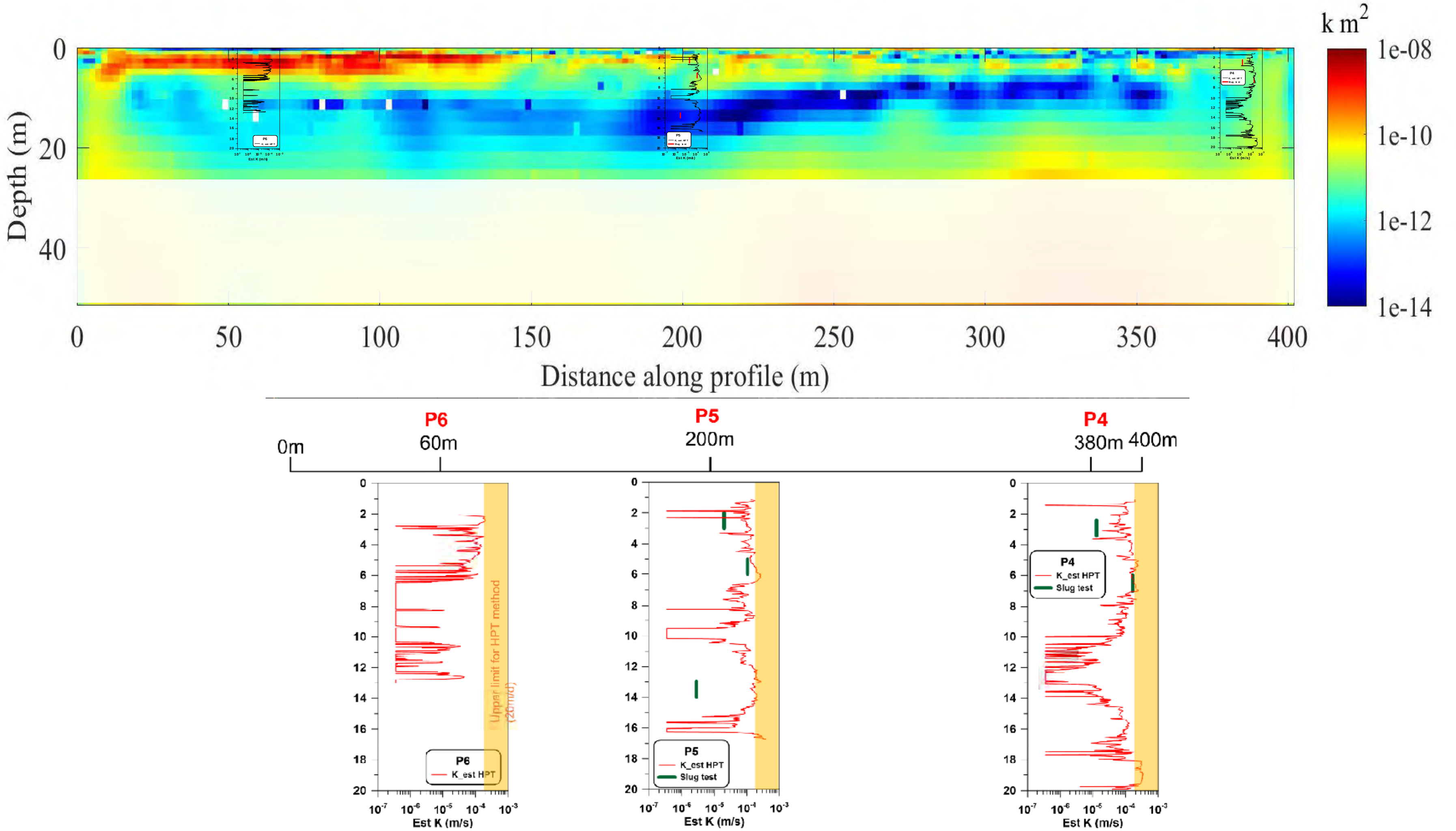


# Comparison – profile 1

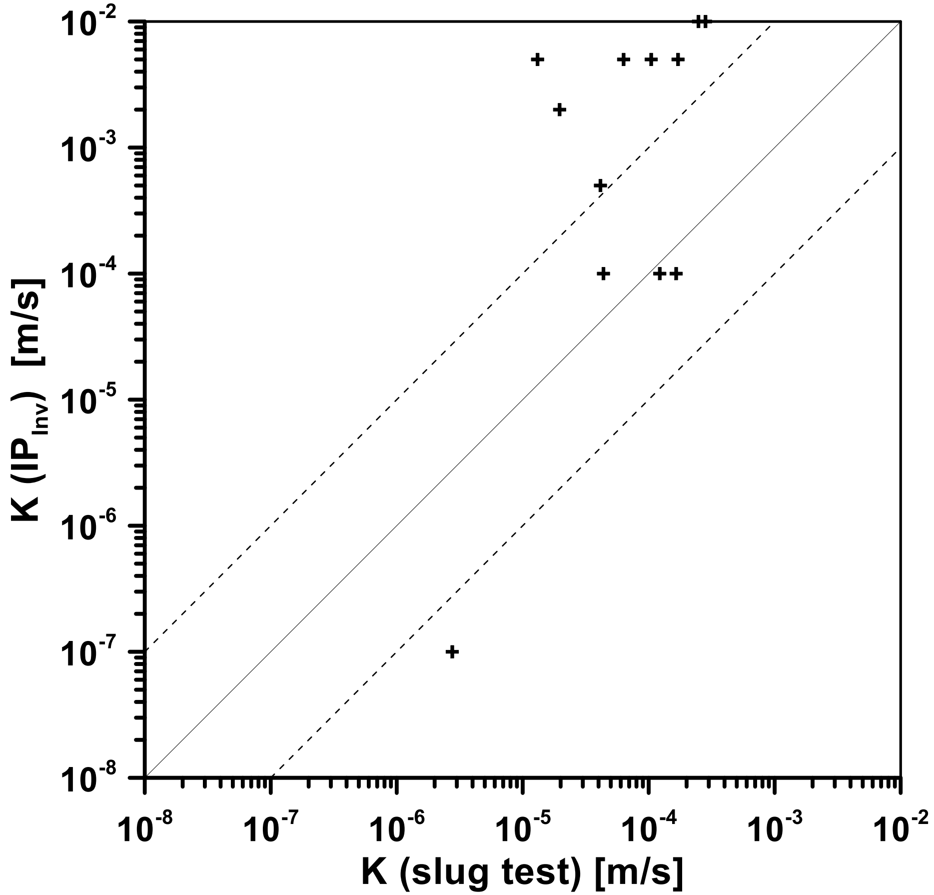


# Comparison - profile 3



# Field measurements conclusion

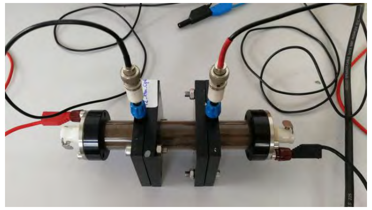


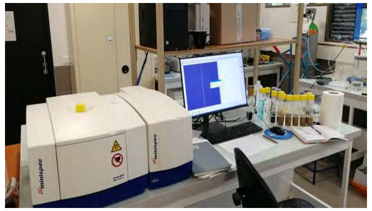

- DCIP and SNMR get good results in the field (**IF** it is not too noisy for SNMR....)
- In general, hydraulic conductivity/permeability can be calculated from IP parameters
- Depends on several factors (equations, saturation, soil conditions, K/k tests…)
- Some correlation with DCIP results – **BUT** not good enough yet

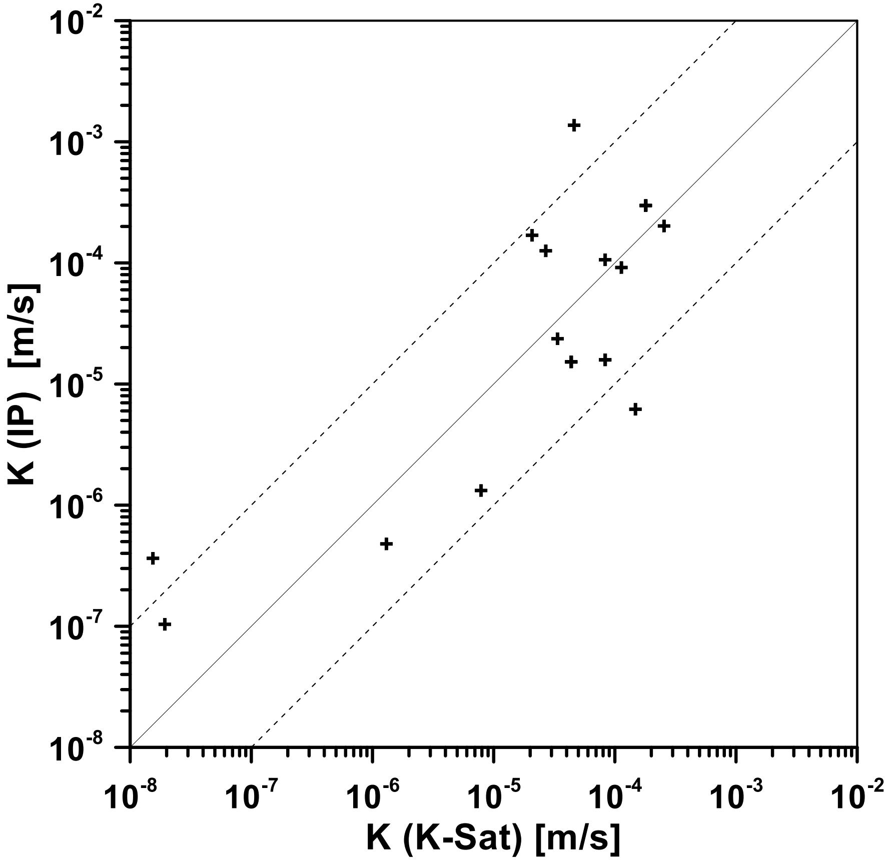
# Laboratory

K-Sat

| Sample | Messmodus | K [m/s] |
|---|---|---|
| Milk_P1_S1-0p5m | CH | 4.36E-05 |
| Milk_P1_S2-0p2m | CH | 8.31E-05 |
| Milk_P1_S2-0p6m | CH | 1.80E-04 |
| Milk_P1_S3-0p2m | CH | 2.08E-05 |
| Milk_P1_S3-0p6m | FH | 1.54E-08 |
| Milk_P1_S4-0p5m | CH | 2.69E-05 |
| Milk_P3_S2-0p6m | CH | 3.37E-05 |
| Milk_P3_S3-0p5m | CH | 4.62E-05 |
| Milk_P4_S1-0p5m | CH | 2.55E-04 |
| Milk_P2_81m-0p5m | CH | 1.13E-04 |
| Sved-siteA-0p2m | CH | 1.48E-04 |
| Sved-siteA-0p6m | CH | 7.86E-06 |
| Sved-siteB-0p5m | FH | 1.93E-08 |
| Sved-siteC-1p15m | CH | 1.30E-06 |








Equation: Knight et al. 2016, Weller et al. 2015

# Final conclusion

- (S)IP and NMR give good results in the laboratory
- The hydraulic conductivity/permeability can be calculated from IP/NMR parameters
- After calibration: good correlation with (S)IP/NMR results (depends on equations, empirical constants, sample holder…)
- But still: ongoing work – new approaches, adaption of previous laboratory equations, more experiments, new projects (borehole investigations), ….

**However, both methods are very promising to obtain spatial hydrogeological properties!**

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# Thank You!

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