

Innovative ZVI application for sustainable remediation of chlorinated solvent plumes

Concept and 5 years of experience

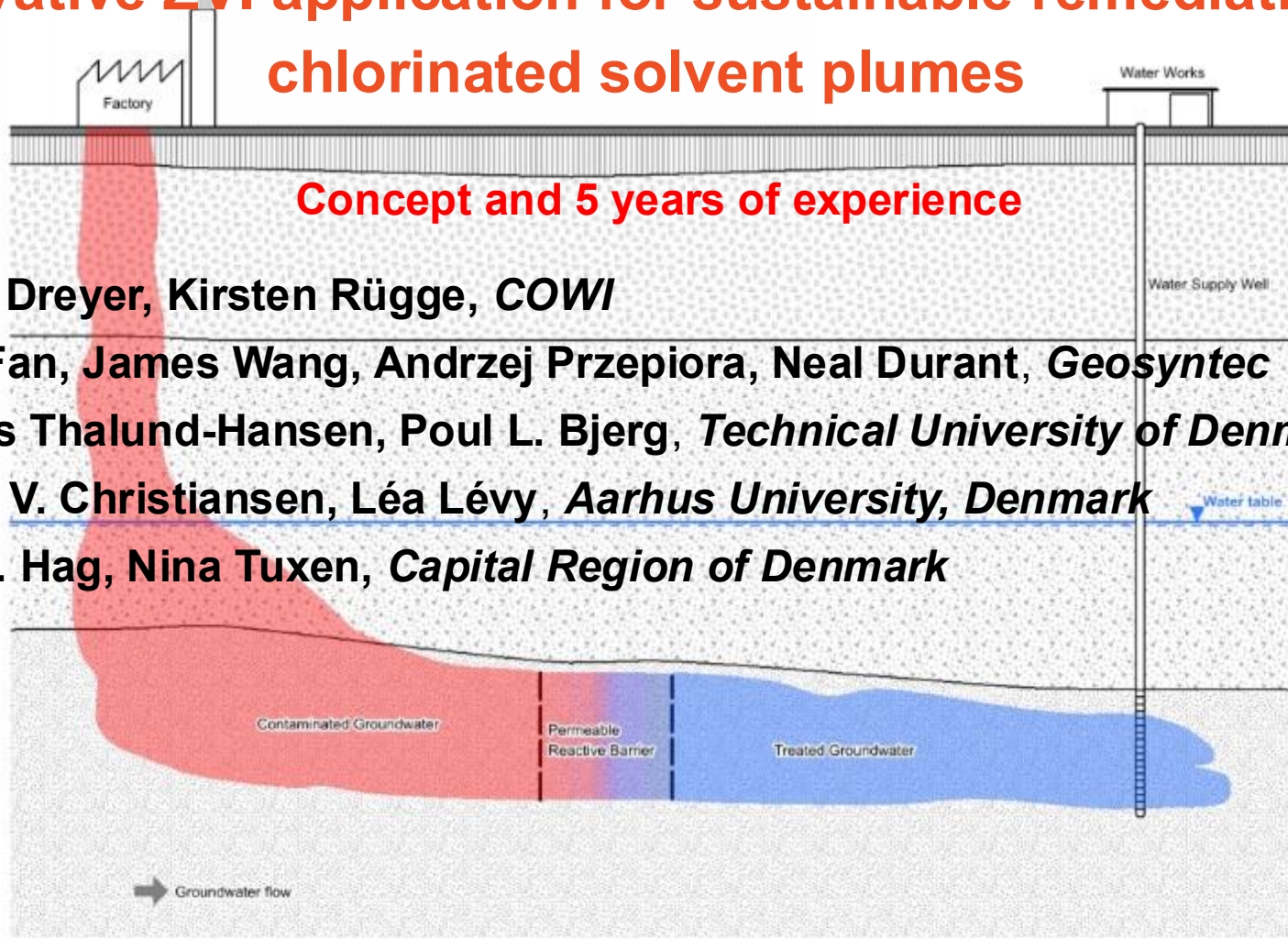
Morten Dreyer, Kirsten Rügge, *COWI*

Dimin Fan, James Wang, Andrzej Przepiora, Neal Durant, *Geosyntec*

Rasmus Thalund-Hansen, Poul L. Bjerg, *Technical University of Denmark*

Anders V. Christiansen, Léa Lévy, *Aarhus University, Denmark*

Maria T. Hag, Nina Tuxen, *Capital Region of Denmark*



Scope of study and 5-year update

Original development objectives

- › Develop a sustainable plume-remediation method
- › Create a PRB with ZVI, organic substrate and KB-1®
- › Document amendment distribution, including DCIP
- › Monitor degradation, longevity, methane and VC

Questions addressed after 5 years

Still effective?

Is treatment capacity maintained downgradient?

What remains active?

How have NVOC, iron and redox conditions developed?

What limits longevity?

Is biological activity becoming donor-limited?

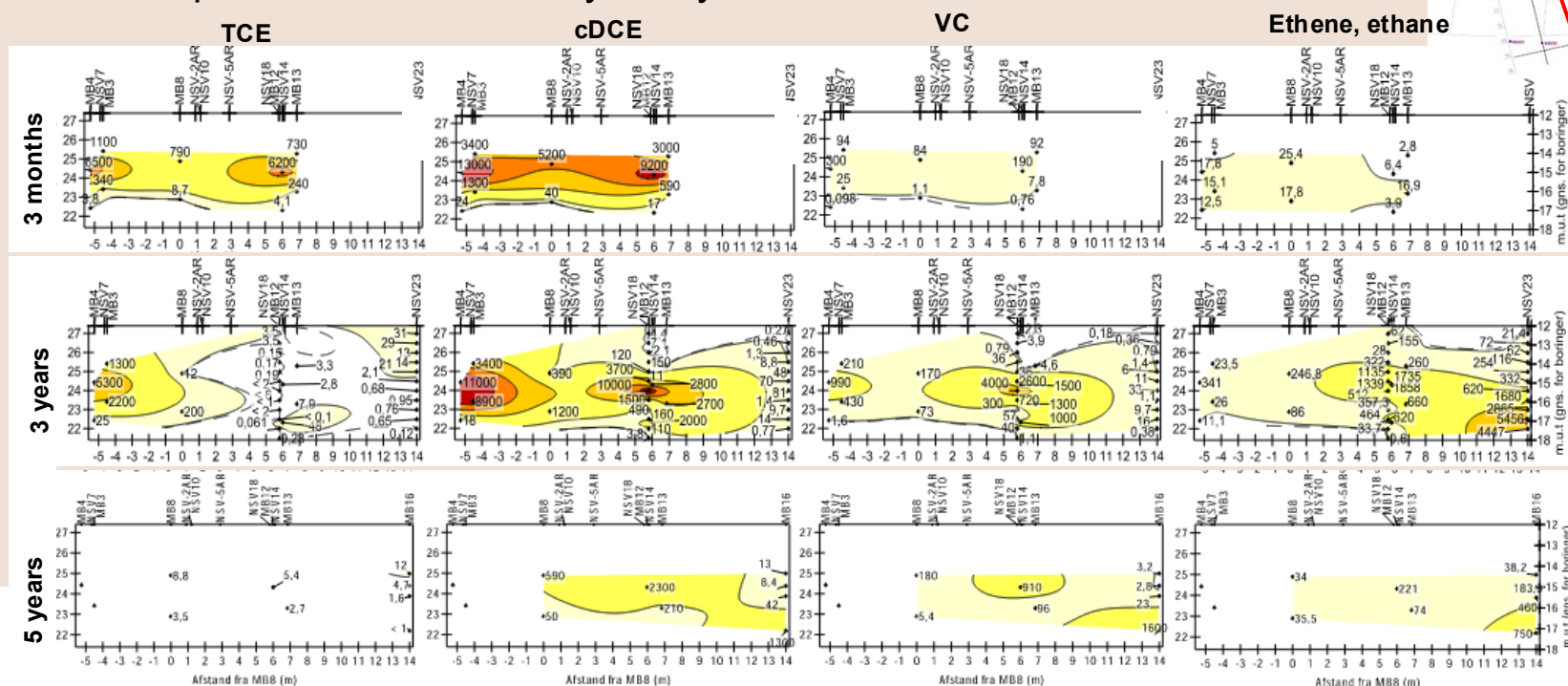
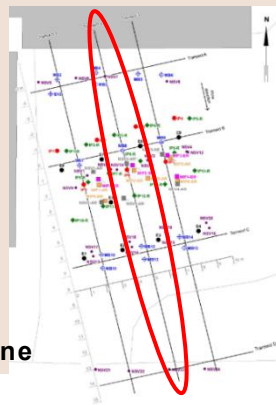
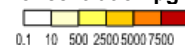
What is transferable?

How should future plume barriers be designed and renewed?

The Reactive Zone Remains Effective After 5 Years

Mean porewater flow velocity 6 m/year

Concentration $\mu\text{g/L}$



Phase 1, laboratory

- Microcosm: five ZVI products (two ZVI-OCs, three S-ZVI products), KB-1[®] culture
- Column: two ZVI products (one ZVI-OC and one S-ZVI) to evaluate treatment longevity and reaction kinetics for design of PRB

Conclusions

- ZVI-OC: Complete degradation of TCE and cDCE after bioaugmentation with KB-1[®] culture
- Design parameters for the PRB obtained

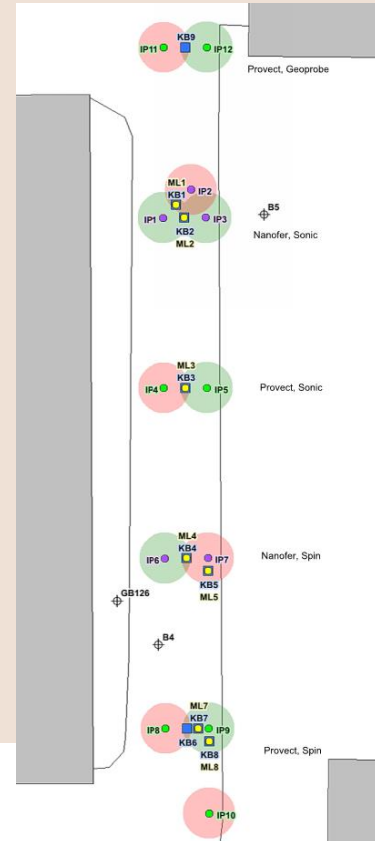


Phase 2, injection test

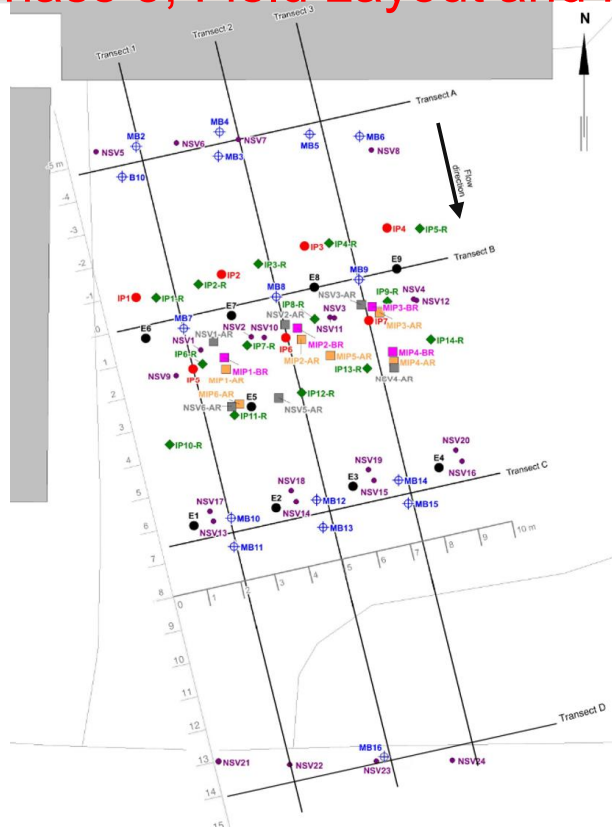
- Three different injection methods: Sonic, Spin[®] injection, Geoprobe DPT
- Two different products

Conclusions

- ROI 0,75 - >1,75 m
- Geoprobe is recommended, top-down
- ZVI-OC is recommended for the PRB



Phase 3, Field Layout and Monitoring Network



LEGEND

-  MBxx Monitoring wells
-  Ex DC/IP electrode boreholes
-  IPx Injection points
-  IPx-R ReInjection points
-  NSVx Depth-discrete groundwater samples
-  MIPx Electrical conductivity (EC) measurements

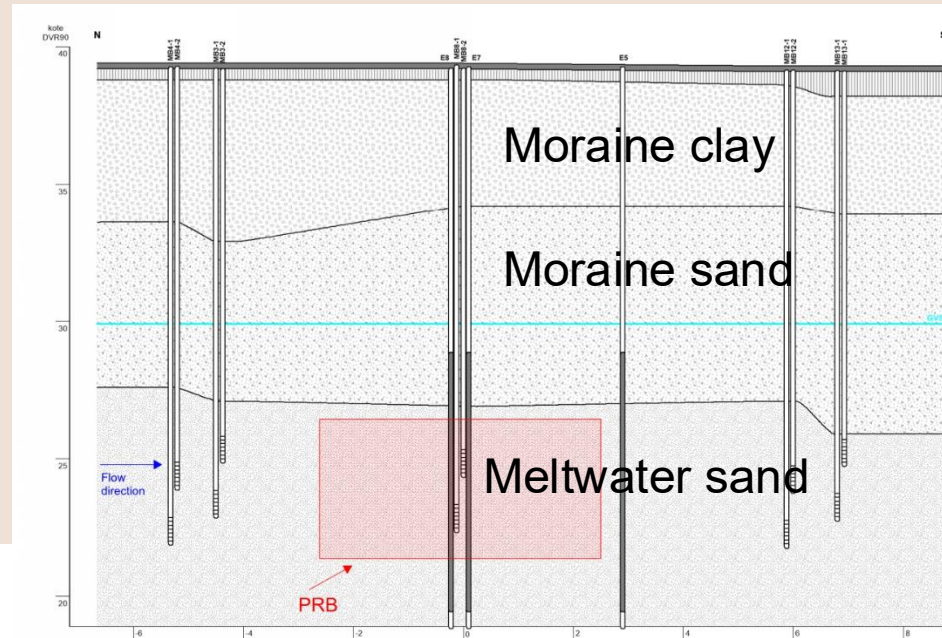
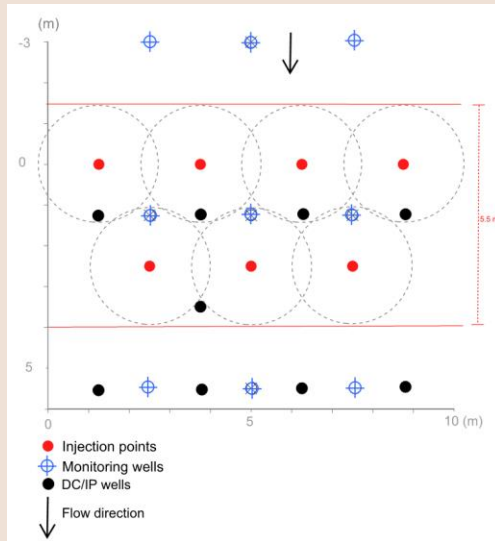
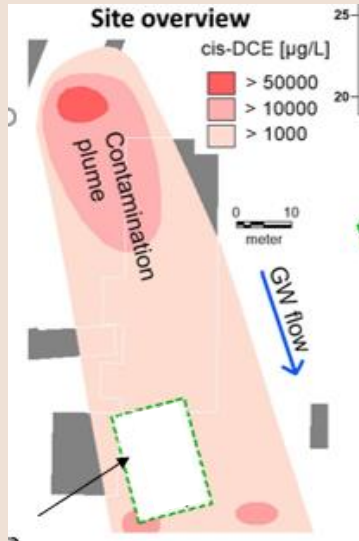
MAP FEATURES

-  Investigation / monitoring transect
-  Groundwater flow direction

Abbreviations: DC/IP=direct current /induced polarization.

Phase 4, PRB

- Creating PRB with ZVI-OC and KB-1[®] culture



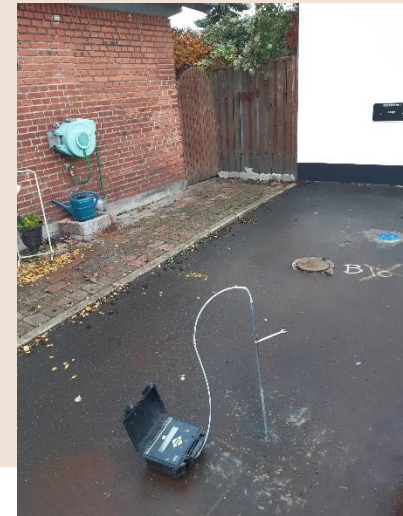
Documentation/monitoring

- **Field measurements**

- Intact soil cores: visual inspection, magnetic susceptibility
- MIP/EC, DCIP
- Groundwater level elevation, pH, oxidation-reduction potential (ORP), electrical conductivity, dissolved oxygen, and temperature

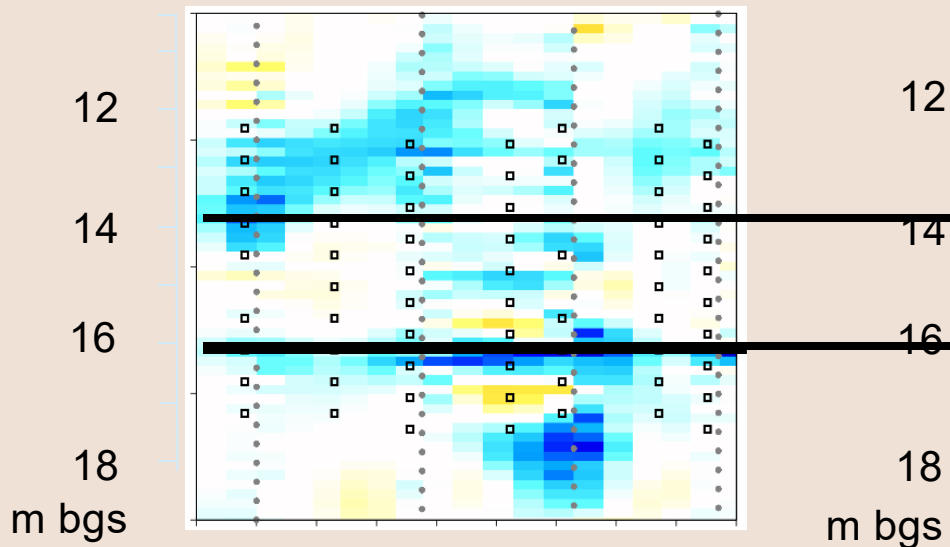
- **Laboratory analyses**

- cVOC concentrations
- Dissolved hydrocarbon gases (ethene, ethane, methane), acetylene
- Metals (including iron, calcium, magnesium, and manganese)
- Anions (including chloride, sulfate, and nitrate)
- Total organic carbon (TOC) and carbonate alkalinity
- CSIA
- Bacterial analysis, *vcrA* etc.
- Fatty acids
- Soil gas



Phase 5, Reinjection and monitoring

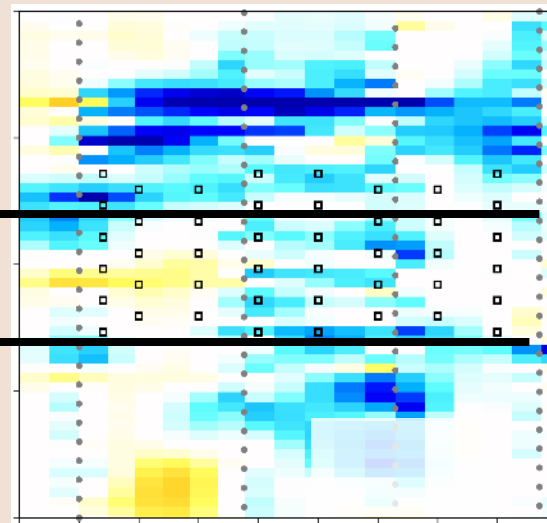
Before reinjection



Conclusion:

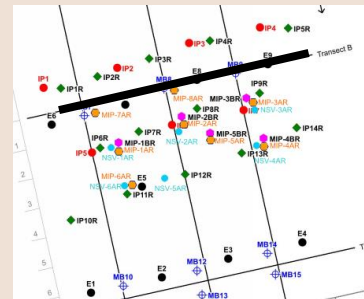
9 Distribution of amendments an issue

After reinjection



Conclusion:

Still an issue?



From installation to 5 (and 7 years) of monitoring



The 5 years event assessed longevity using CVOCs, NVOC, iron, sulphate, redox, methane and VC in the GW flow direction

5 years: the amendments are ageing

NVOC

Back around baseline in much of Transects B, C and D. Less substrate means declining biological degradation.

Iron

Back near baseline in Transects B and C but still elevated at Transect D which could be evidence of potential abiotic degradation.

Redox / sulphate

Reduced conditions remain.
ORP values from -130 to -77 mV, which means that we still have good conditions for degradation of CVOCs.

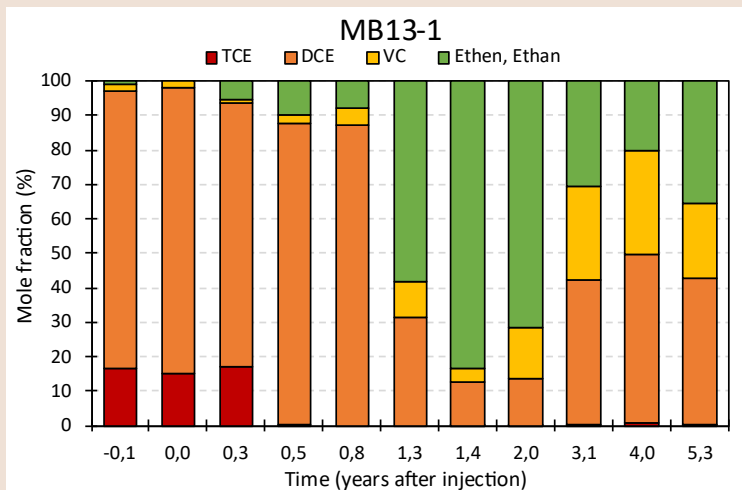
High initial amendment conc.

transport + consumption over
time

weaker biological support

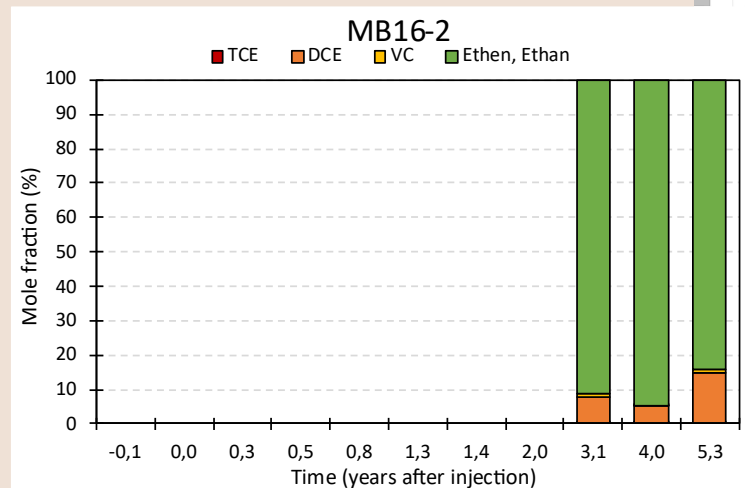
Degradation is still occurring, but at a lower rate than when the PRB was most active

5 years: treatment capacity is still present



Transect C

DOD ca. 60%



Transect D

DOD up to 97%

Degree of Dechlorination demonstrates that the contaminant mass is progressively shifted towards ethene and ethane along the groundwater-flow direction.

Conclusions after 5 years

1

Treatment capacity remains

Sufficient capacity has been maintained to treat CVOCs to low concentrations downgradient.

2

The reactive zone is longer

Full degradation becomes most visible between Transects C and D.

3

Biological support is ageing

NVOC is near baseline, so declining bacterial activity is expected.

4

Abiotic activity persists farther downgradient

Iron remains elevated at Transect D and degradation continues.

5

Multiple lines of evidence

Supports a PRB longevity of at least 5 years, but the limiting process is shifting from distribution to substrate availability

Take home messages for NORDROCS 2026

Combined treatment works

ZVI-OC with KB-1® remains a promising plume-remediation approach.

Contact time compensates for imperfect distribution

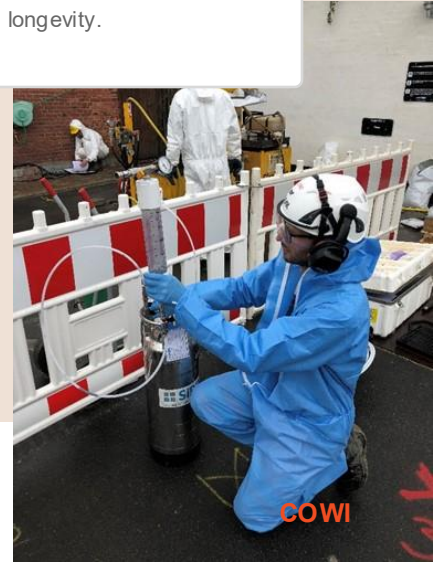
Complete degradation was observed farther downgradient.

Multiple lines of evidence are essential

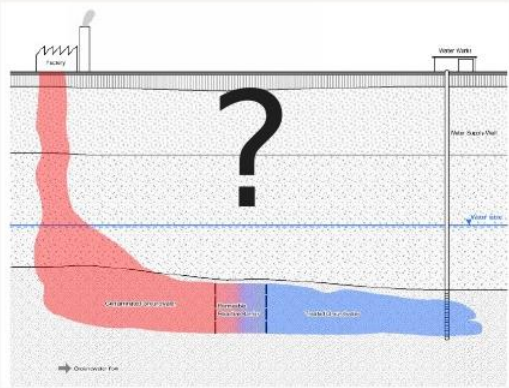
Chemistry, DOD, CMD, gases, geochemistry, microbes, CSIA and DCIP explain different parts of the system.

Design for renewal

Iron and organic substrate do not have the same longevity.



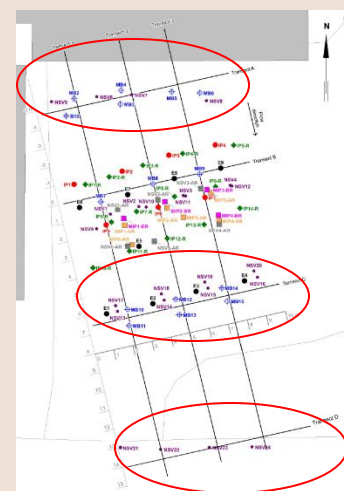
Challenges



Extra slides

Contaminant mass discharge

sum, cVOC	Transect A (mol/year)	Transect C (mol/year)	Difference (A-C) (%)	Transect D (mol/year)	Difference (A-D) (%)
Baseline	4,3	4,5	5	-	-
3 months after	4,2	4,6	8	-	-
9 months after	5,9	3,8	-35	-	-
15 months after (baseline before reinjection)	6,0	3,9	-34	-	-
24 months after	5,0	3,1	-38	-	-
36 months after	7,0	3,4	-51	0,5	-93



Extra slides

- DOD of TCE is determined using the molar concentrations ($\mu\text{mol/l}$) of each degradation product in the following equation.
- $$DOD (\%) = \frac{DCE + 2 \cdot VC + 3 \cdot Ethene + 3 \cdot Ethane}{3 \cdot (TCE + DCE + VC + Ethene + Ethane)} \cdot 100$$

Degree of Dechlorination demonstrates that the contaminant mass is progressively shifted towards ethene and ethane along the groundwater-flow direction.

