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sustainable tomorrow

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***Selection of the BAT for the reduction of
chlorinated solvents in groundwater, based on a
thorough understanding of the site,
complementing remediation works with
targeted monitoring***

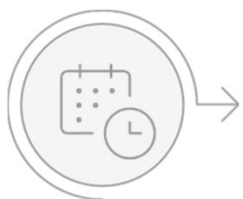
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Innovative Soil Remediation Solutions
October 7, 2026 • 14:20 CEST • Innovative solutions – Nature-based - Bioremediation

Historical usage



- ▶ Use of chlorinated solvents in the machining process of metal parts
- ▶ Impact on the soil through spills, leakages, etc., resulting from industrial activities over the years

Environmental hazard



- ▶ Chlorinated solvents are widely known to be hazardous to the environment because they are persistent, toxic compounds that can contaminate soil and groundwater and may migrate over long distances

Restoration strategy



- ▶ Especially in a fractured bedrock medium, it is unlikely to make a reliable approach without properly understanding the conceptual site model



Case study - why the case matters

- ▶ Historical metal degreasing generated a groundwater plume dominated by TCE and its reductive daughter products
- ▶ It is difficult to understand the site's hydrogeological setting, given the presence of groundwater filtrations, local groundwater flow pathways, and extensively fractured bedrock across a wide area
- ▶ The site does not remain operational, but a new activity is about to begin, so the remediation had to minimise disruption, waste generation and permanent infrastructure



Objective

How can a durable in situ remediation be designed for a shallow, heterogeneous fractured-rock system?

Soil drilling example

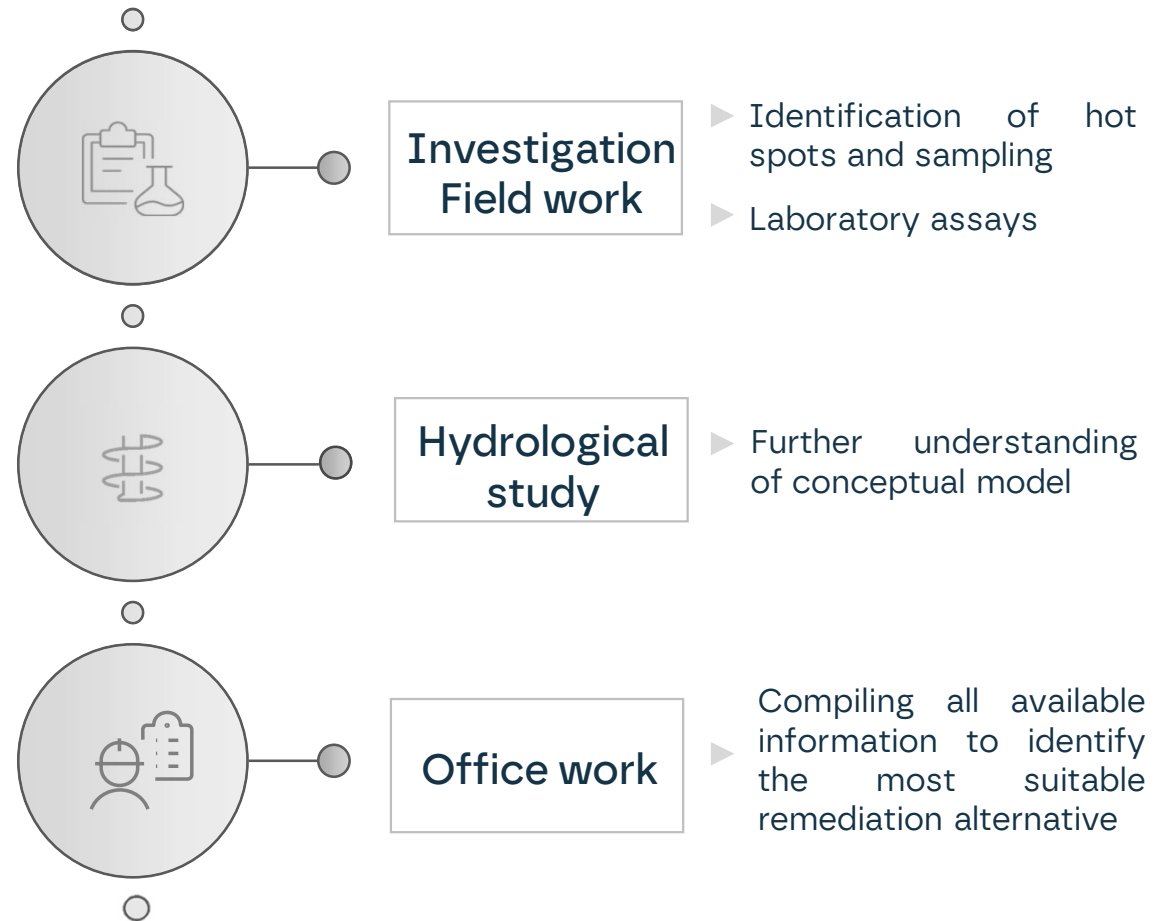
Unsaturated zone



Saturated zone



Methodology



Deep field work established the conceptual site model

- ▶ Soil, groundwater and soil-gas investigations determined sources, plume margins and vapour conditions
 - ▶ 48 piezometers with different depths and construction lay-outs
 - ▶ 18 soil vapour sampling points
- ▶ The hydrological study differentiated the permeable fracture layer from the low-permeability rock matrix. The study included pumping, injection and permeability tests
- ▶ Two source areas sustained impacts across the central factory area
- ▶ Groundwater levels, field chemistry and laboratory analyses provided the basis for a remediation



Importance of full understanding of the conceptual model

Characterisation reduced design uncertainty before full-scale injection

The hydrological study gave us some crucial input:

- ▶ Water table: 1.3–4.1 m below ground level, generally within bedrock
- ▶ Upper bedrock: highly fractured. Fracturing decreases markedly from approximately 3.2–4.3 m depth
- ▶ Practical impermeability: assumed from approximately 9 m depth
- ▶ Preferential groundwater flow: west–southwest, with a local depression around P14



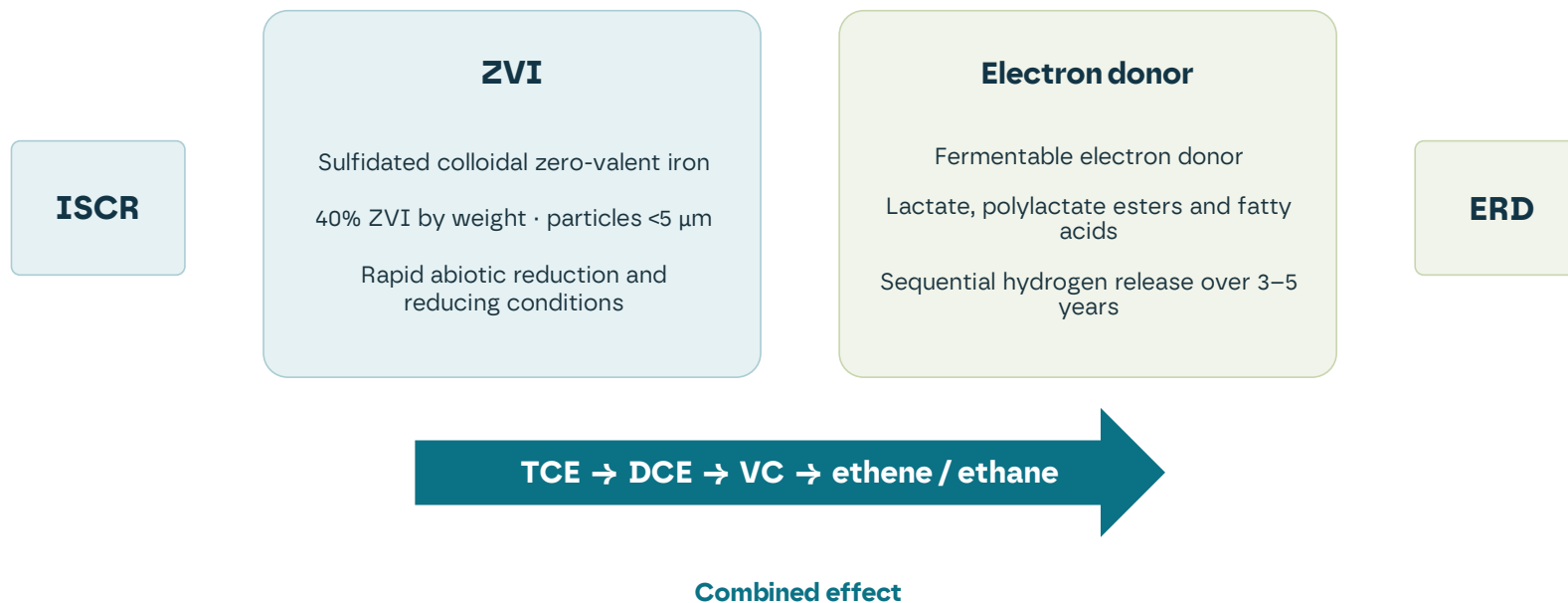
Design implication

Treatment must intersect connected fractures while accounting for matrix storage and back diffusion

Best available technology (BAT) selection prioritised contact, longevity and operational compatibility

Screening criterion	Pump and treat	Thermal / oxidation	ISCR + enhanced anaerobic dechlorination
Fractured-rock contact	Limited by capture zones	Distribution and infrastructure constraints	Colloidal amendments can enter transmissive fractures
Treatment of parent and daughter compounds	Long operating period	May require repeated campaigns	Complementary abiotic and biological pathways
Persistence / back diffusion	Rebound risk	Shorter reaction window	Electron donor and ZVI designed for multi-year activity
Operational footprint	Permanent plant and energy demand	Higher site disruption	Low-pressure injection with no permanent plant

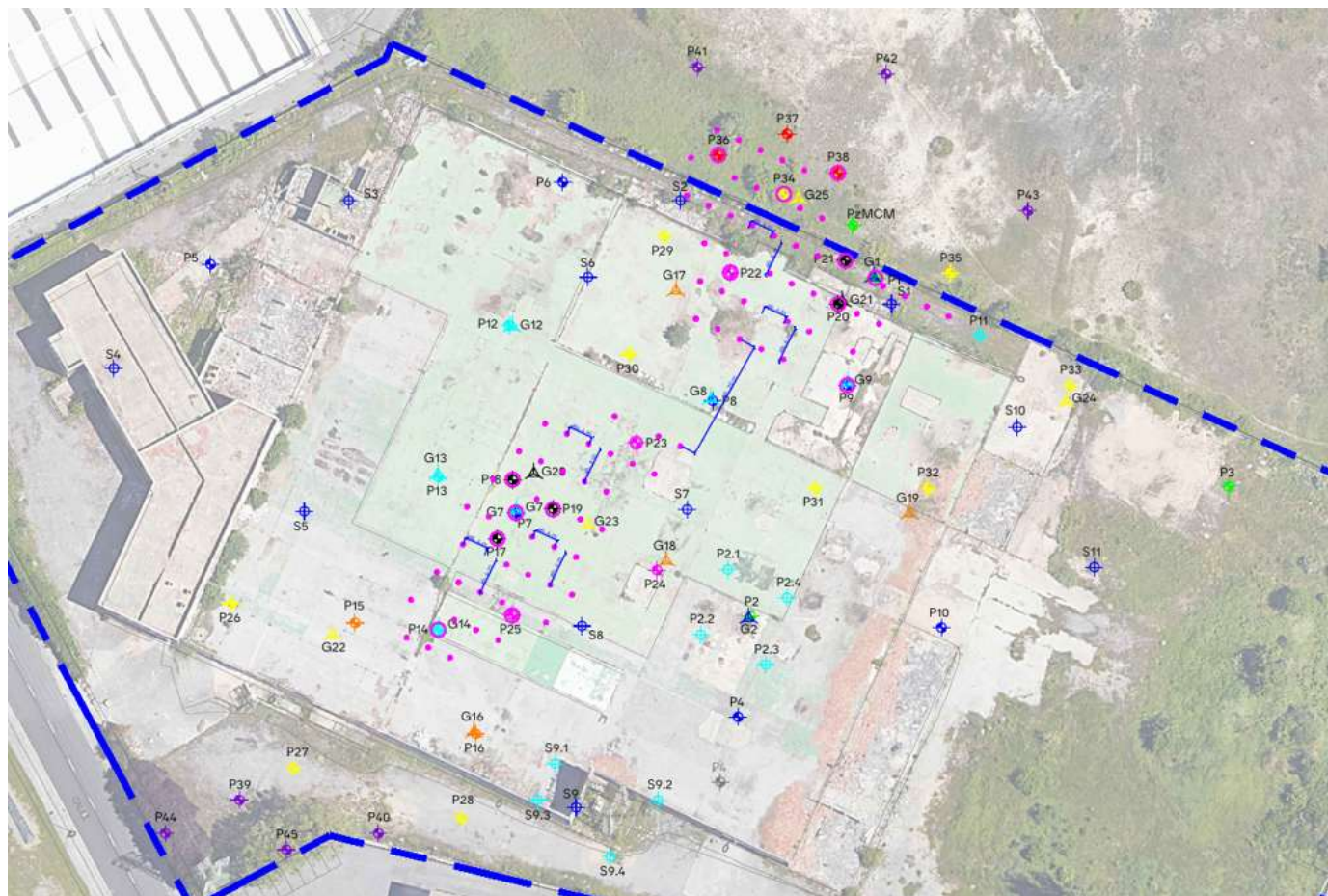
The selected BAT couples rapid abiotic reduction with sustained electron donation



Fast parent-compound destruction plus sustained biological polishing of residual and desorbing mass



Office work – Full scale design



98 injection wells

83 new 3-inch wells

15 existing wells reused

2.5–5.0 m screened treatment interval

4 × 6 m nominal grid

1,050 L injectate per location

Per well: 90 kg e⁻ donor + 75 kg ZVI



Field implementation used a mobile mixing unit and pneumatic injection system



- ▶ Injection works took place during weeks 51–52 of 2024 and week 2 of 2025
- ▶ 2 mobile mixing units + injection pneumatic pumps through pneumatic packers were used
- ▶ Fresh water supplied for reagent dilution & mixing. Portable tanks supported periods of high demand
- ▶ Pressure and distribution were controlled to manage preferential flow in the fractured medium

Groundwater & gas monitoring

Performance network

23 wells

CVOC analysis & monitoring of in situ parameters every 6 months

12 soil-gas points

CVOCs and static PID measurements

Lines of evidence

TCE, cis/trans-DCE and VC quantify the sequential dechlorination pathway

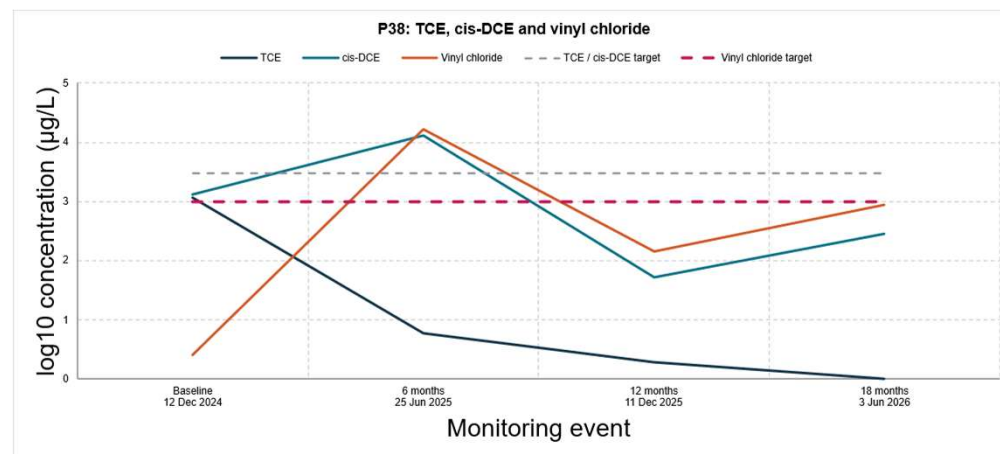
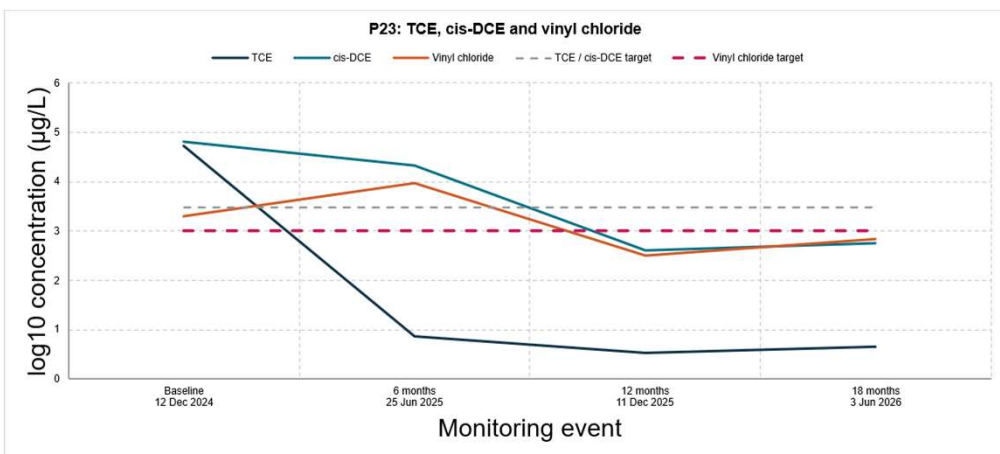
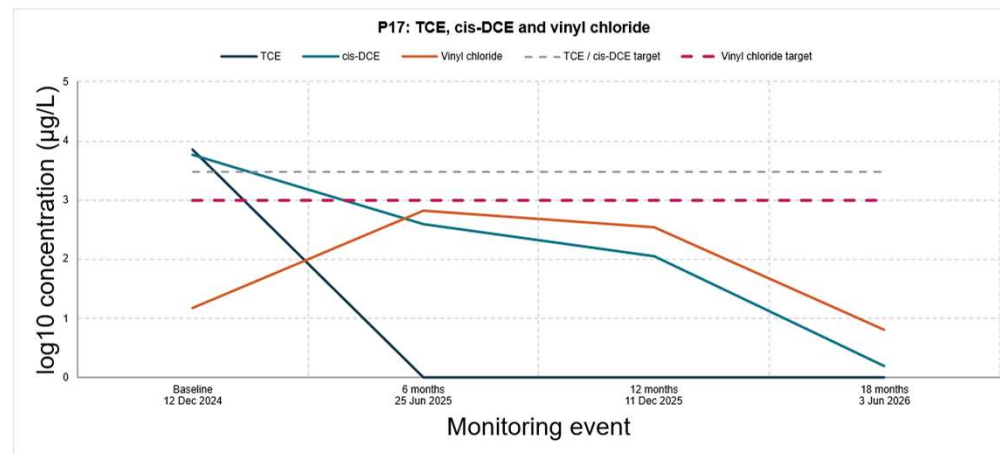
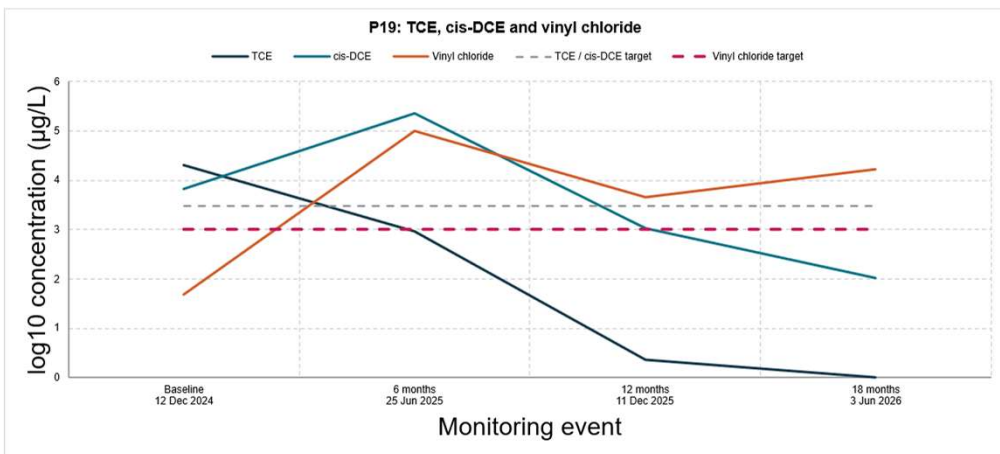
ORP, pH, organic matter, nitrate, sulphate, iron and manganese track reducing conditions and competing electron demand

Analysis of taxonomic composition of the microbial community confirms if the intended biological response develops



Three post-injection campaigns available at 18 months

Field monitoring - results





Field monitoring - results

Latest available results vs. site-specific targets

22 / 23

TCE wells at or below 3,000 µg/L

17 / 23

cis-DCE wells at or below 3,000 µg/L

14 / 23

VC wells at or below 1,000 µg/L

Interpretation

TCE decreased by more than 90% from baseline

Transient DCE and VC peaks demonstrate active sequential dechlorination and redistribution of contaminant mass

The reagents remain active beyond the current monitoring horizon, so final performance cannot yet be inferred from 18-month data alone

Latest available results vs. site-specific targets

Observed pattern

Strong TCE removal demonstrates reagent contact and rapid reductive capacity in treated zones

DCE and VC peaks vary between wells, reflecting fracture connectivity, local mass transfer and incomplete treatment coverage

Some wells out of the injection area require particular attention because their position limits direct reagent contact

Next monitoring decisions

- 1 Repeat full CVOC and geochemical campaign
- 2 **Apply compound-specific isotope analysis at selected wells**
- 3 Reanalyse the microbial taxonomic composition and further explore the measurement of functional genes
- 4 Use evidence to choose continued monitoring or local reinjection

Decision rule

Continue monitoring

when parent compounds remain controlled and daughter-product trends decline under reducing conditions

Targeted reinjection

when persistent mass coincides with incomplete coverage or insufficient reagent contact

Conclusions

► **Characterisation drove technology selection**

The fractured-rock conceptual model justified an injectable, persistent remediation and defined the treatment interval

► **Complementary mechanisms improved robustness**

ZVI supplied rapid abiotic reduction while the e^- donor sustained enhanced anaerobic dechlorination

► **Implementation matched the operational setting**

98 injection wells provided broad coverage without permanent plant or major disruption to future operations

► **Deep monitoring demonstrates progress and remediation control**



Core idea

A defensible remediation decision emerges from the combined weight of spatial, chemical, geochemical and microbiological evidence & deep monitoring provide strong certainty



Thank you for your attention!



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