Innovative Technologies for Recovery of Industrial Sites

- Groundwater Remediation

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Structure

- Basics: Groundwater flow in aquifers
- Innovative methods of groundwater remediation
- Problems and difficulties
- Recommendation: Hydraulic control of vertical flow in aquifers

Basics:

Groundwater flow in aquifers

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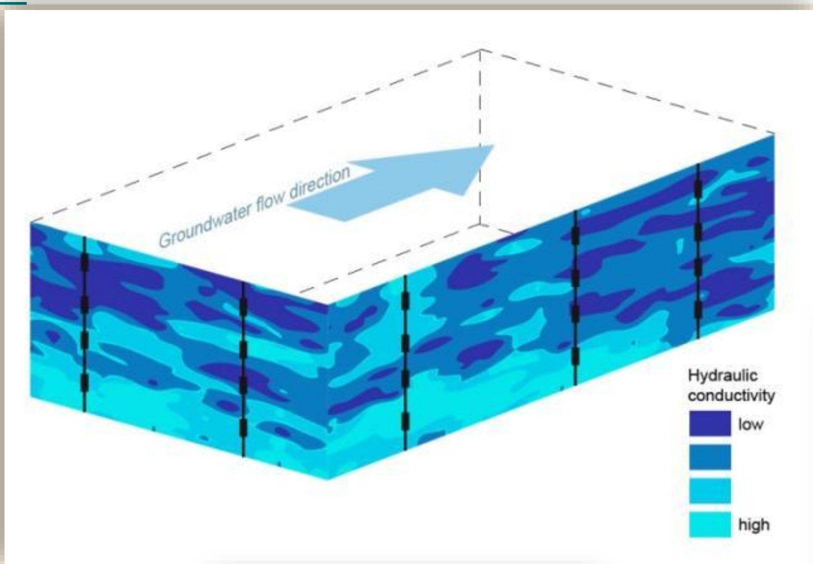
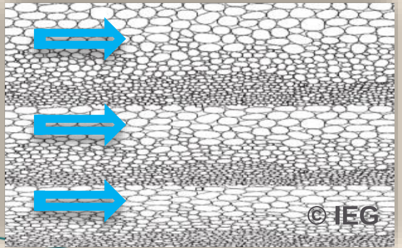
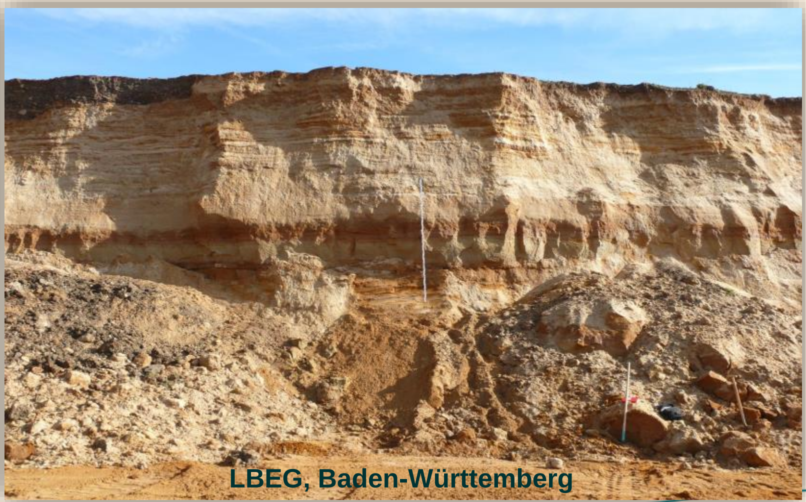




Natural sedimentation leads to a complex layered, porous medium. Due to its structure, fluid movement has preferential directions (regulary horizontal)



Basics: Groundwater flow in aquifers

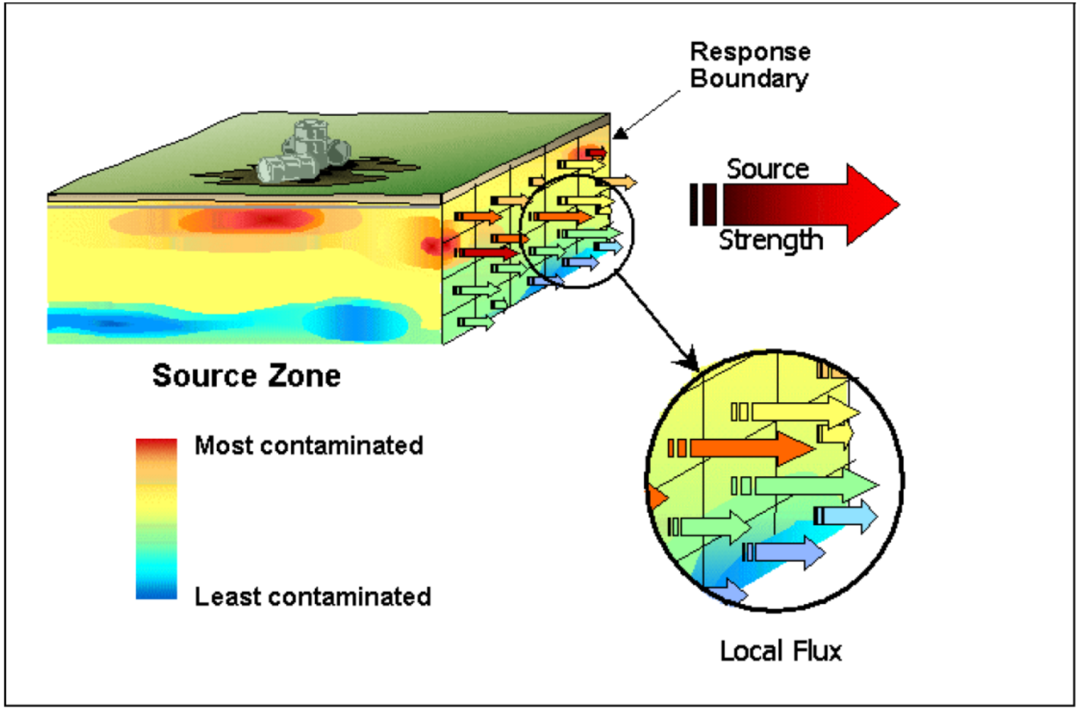


Figure 1-2. Response boundary in relation to the source zone.
(*Source:* Wood et al. 2004)

Groundwater moves on preferred horizontal flow paths with different pollution loads. Depth-differentiated monitoring wells are essential for proper estimation of environmental risks.

Innovative methods of groundwater remediation

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What are the latest developments in groundwater remediation research and application?

- Microbiological degradation of organic pollutants
- Thermally supported remediation
- Hydraulic control of vertical flow in aquifers
- Biosurfactant application
- Foam fractionation for PFAS removal
- Pulsed Direct-Push-Technologies (biotic/abiotic)
- In situ chemical oxidation (ISCO)

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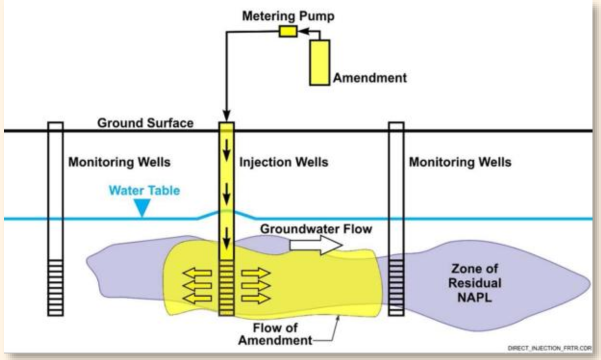
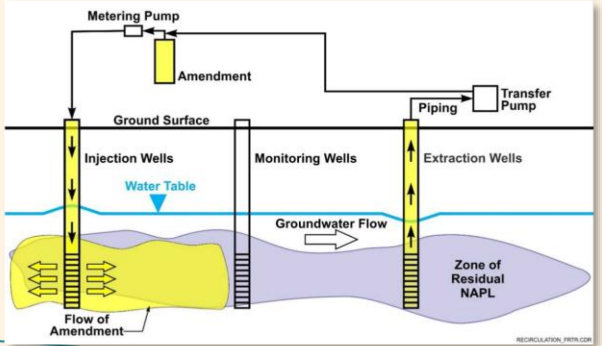
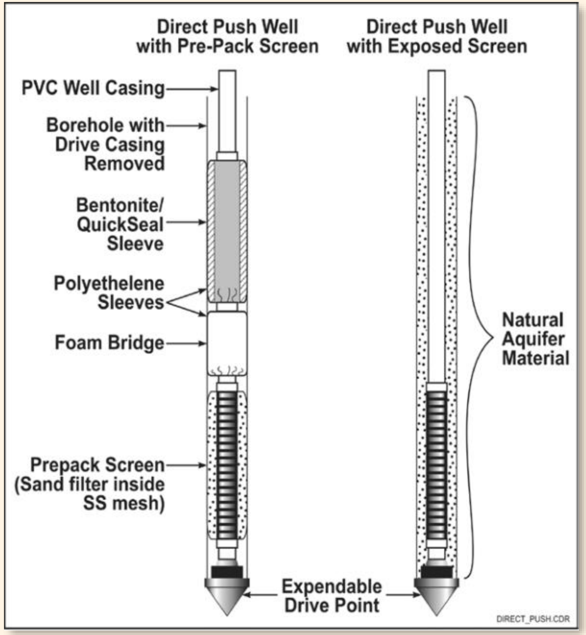
Common techniques and tools for groundwater remediation







NAFAC Technical Report 1303, 2023

Principles of bioremediation

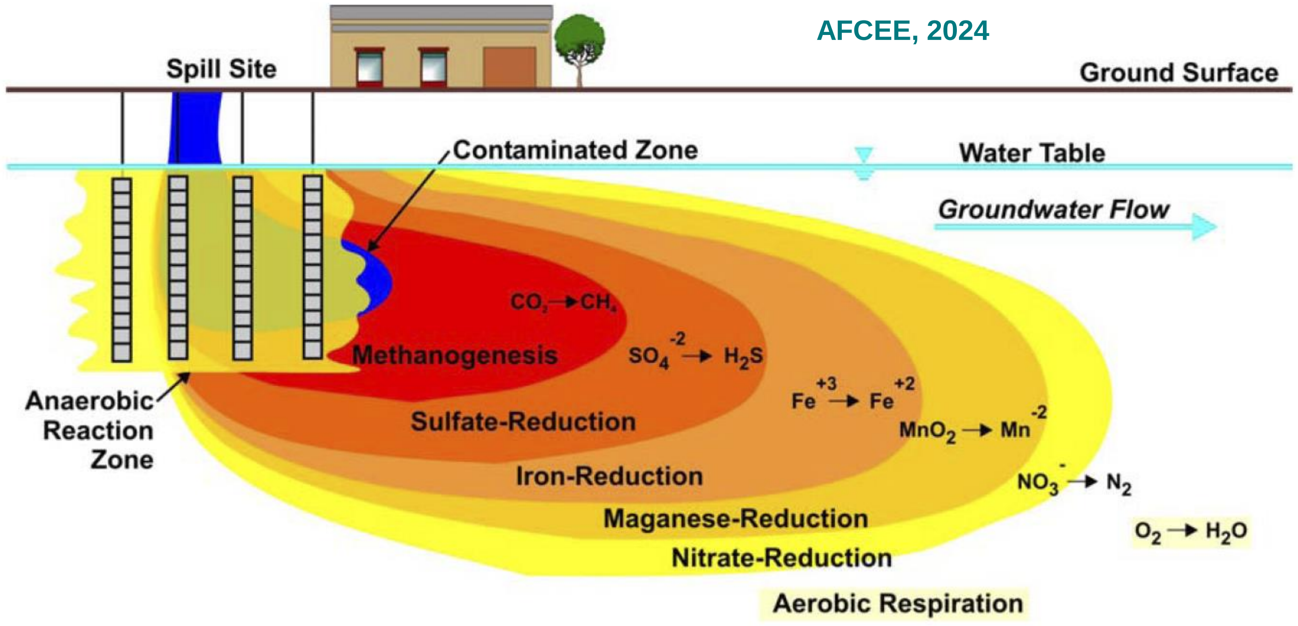
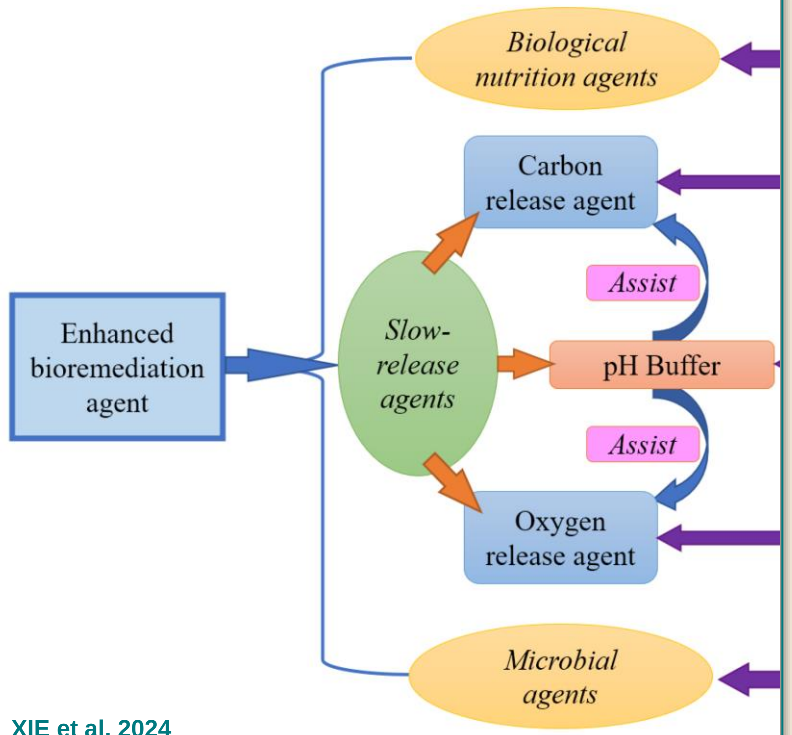


Figure 1.3 Reducing Zones Established Downgradient of Substrate Injection

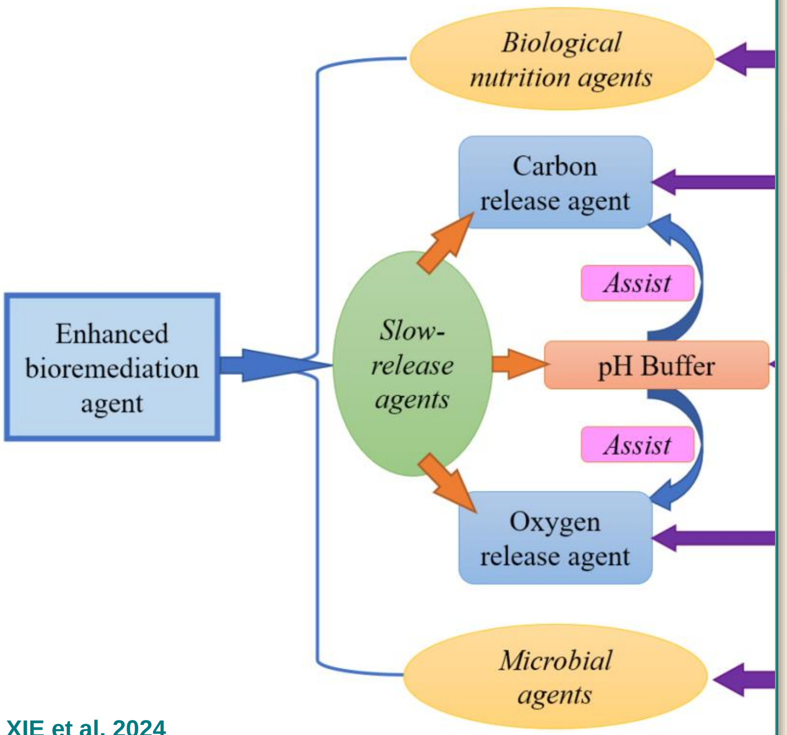
Innovative methods of groundwater remediation



XIE et al, 2024

Mainly contains inorganic salt for biological growth and improving reproduction rate

Innovative methods of groundwater remediation



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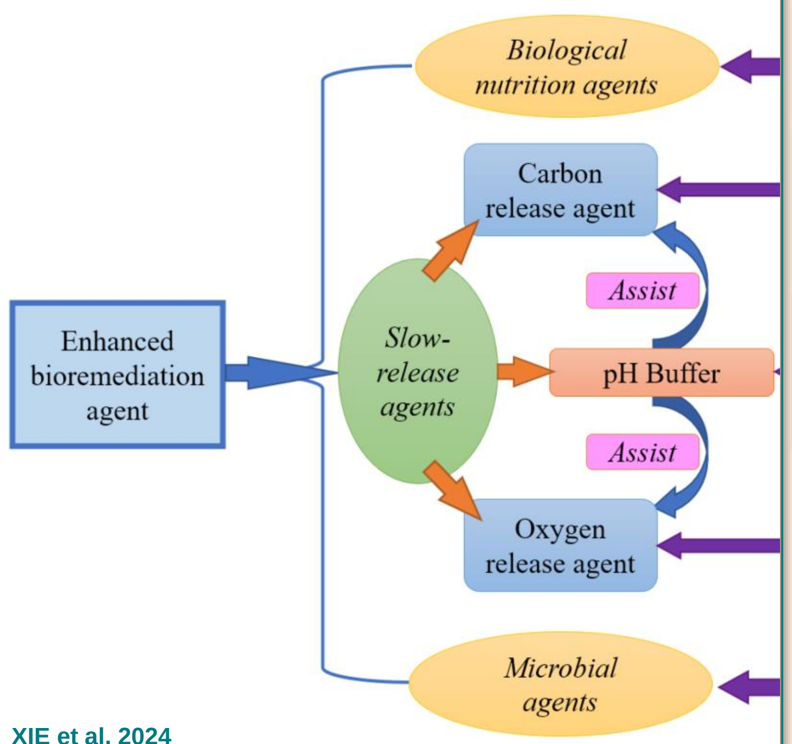

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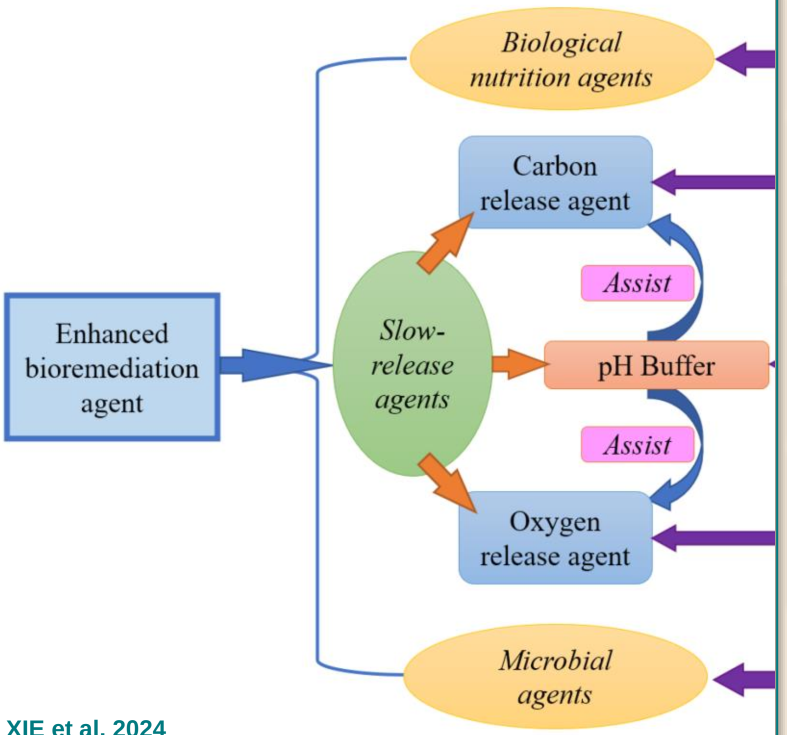

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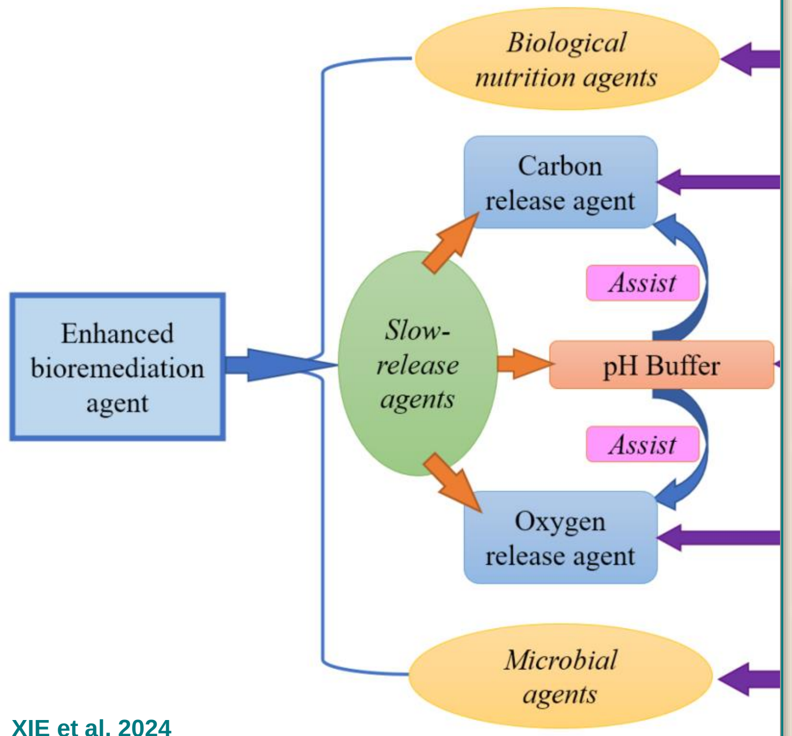

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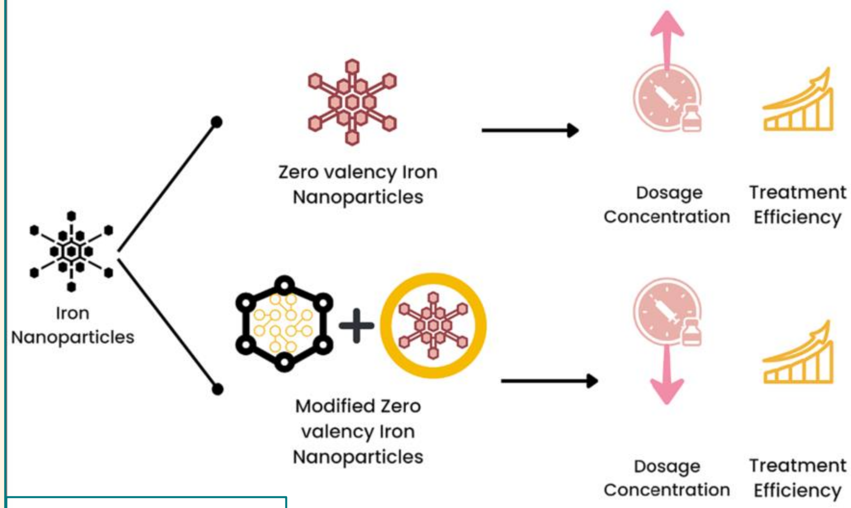
Specialized microbial communities extracted and propagated from contaminated sediments or sludges; they increase the amount of degrading microbacteria in the subsurface

Abiotic remediation



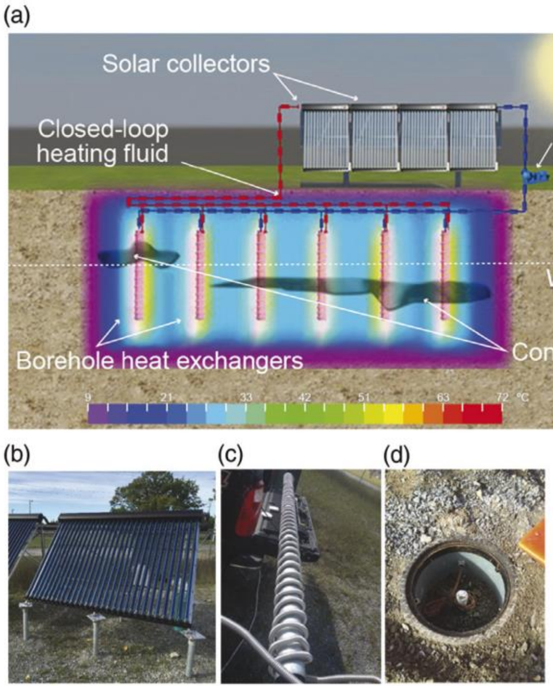
SATHISH et al, 2024

nZVI (nanoscale zerovalent iron)

Non-toxic electron donors for the treatment of halogenated organic compounds and some heavy metals (e.g. Chromium, Uranium)

nZVI particles or composite materials cause abiotic reductive dechlorination of pollutants

Innovative methods of groundwater remediation



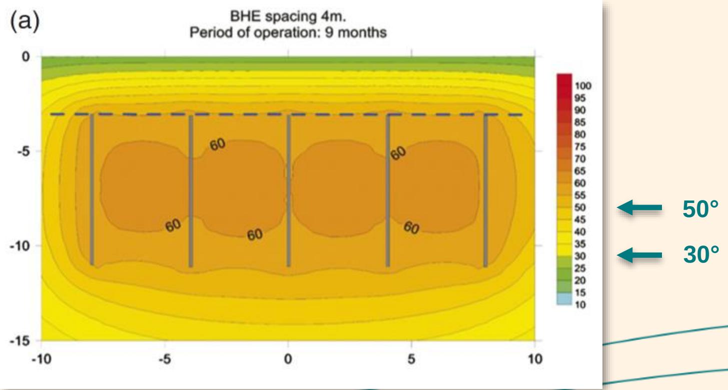
HORST et al., 2016

Figure 5. TISR™ System schematic at top, with photographs of the solar collectors (a), an early version of the borehole heat exchangers (b) and the thermocouple (c).

Thermal In-Situ Sustainable Remediation (TISR™) system

The system increases the temperature in groundwater and thus significantly increases biodegradation

A 10°C increase in groundwater temperature enhances biological activity by a factor 2 to 3



Problems and difficulties

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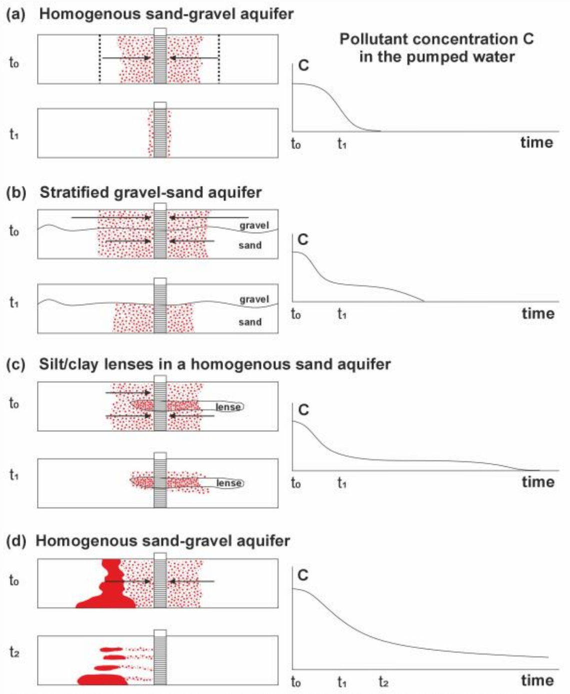
Significant reduction in pollutant levels with elimination of the source



In each of the cases a) to d) the same amount of water is removed. The dashed line in a) represents the volume of water pumped out for flushing out NAPL (assumed retardation factor 2) from the homogenous aquifer.

NAPL-Phase (= *non-aqueous phase liquids*, e.g. LHKW)

NAPL in dissolved and sorbed phase originally evenly distributed

→ Relative groundwater velocity

©IEG, modified after EPA/600/R-94/123

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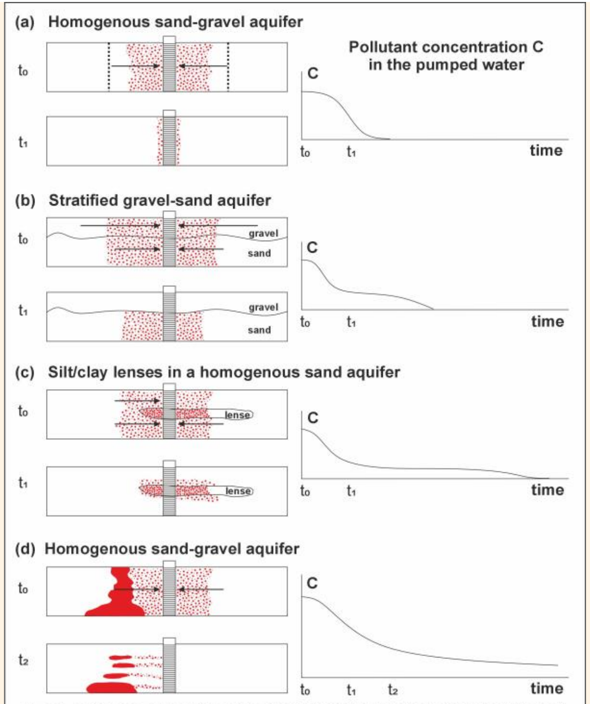
Two-layered aquifer (gravel on top, sand below): after rapid decline, significant delay in reduction



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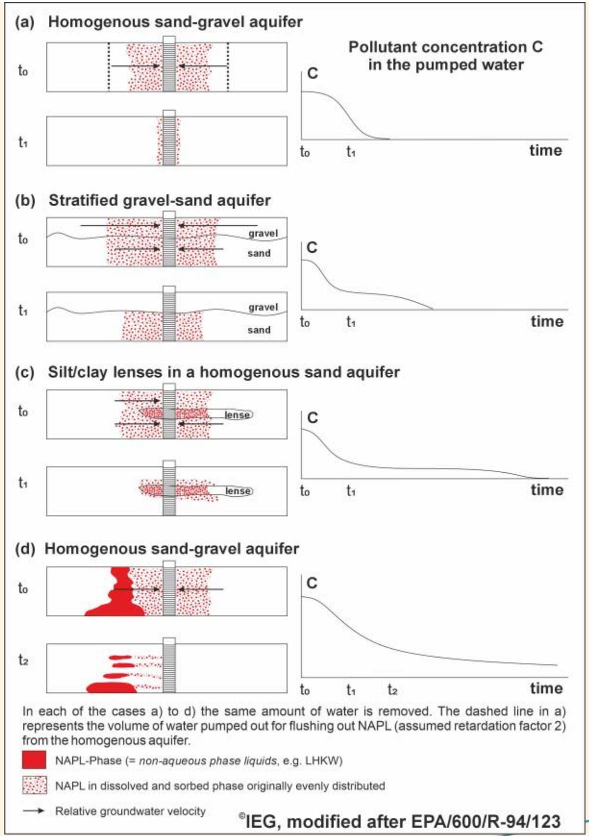
Horizontal fine grain structures leads to a delay in the reduction of pollutants for a long time



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Two-layered aquifer (gravel on top, sand below): after rapid decline, significant delay in reduction

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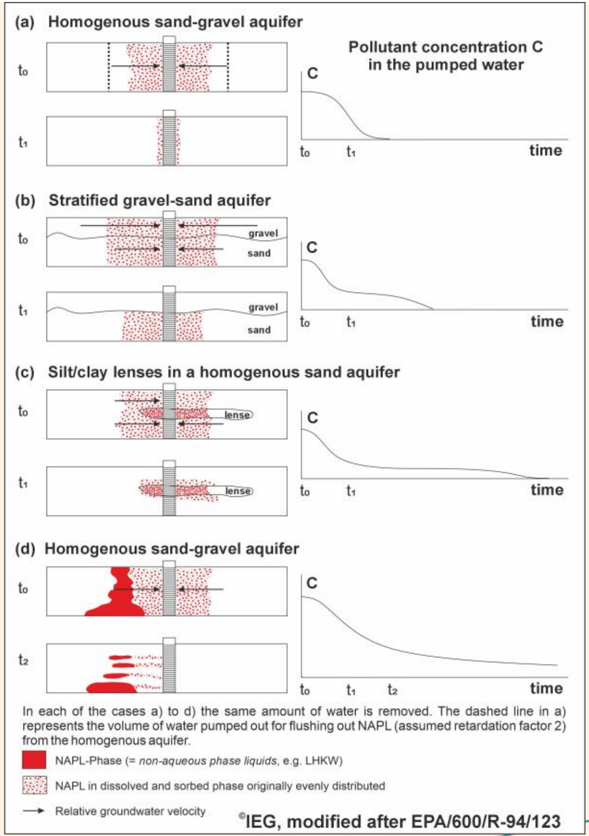
Residual phase in the aquifer: P&T unsuitable, remediation target only achievable in decades



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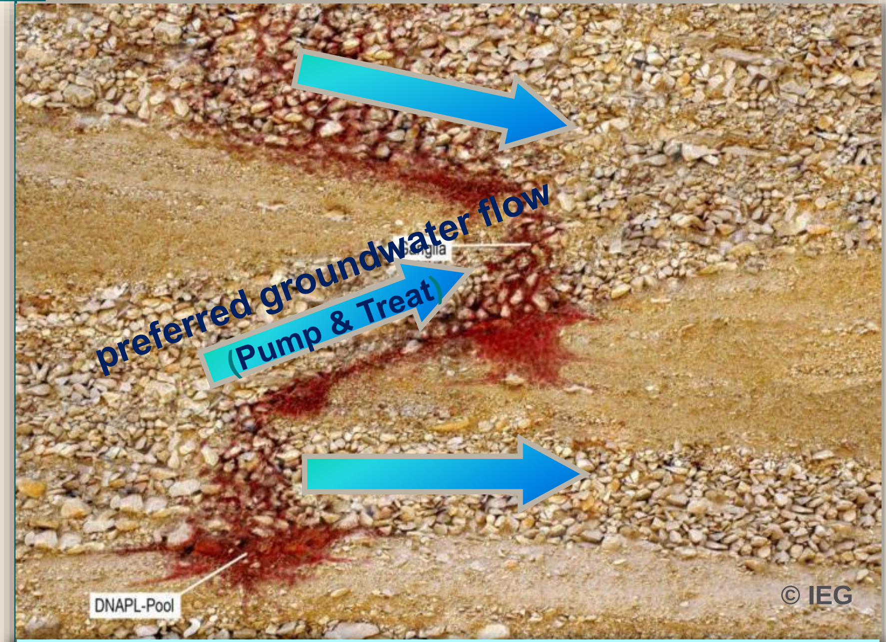
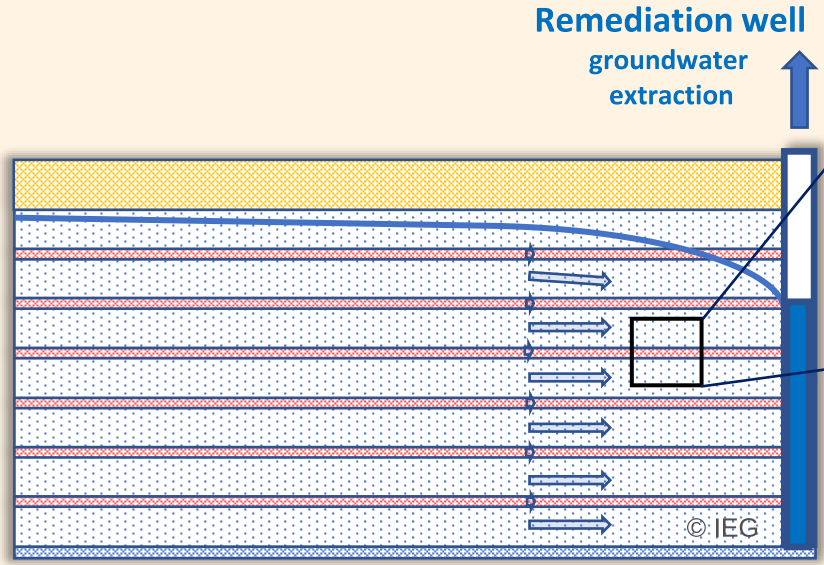


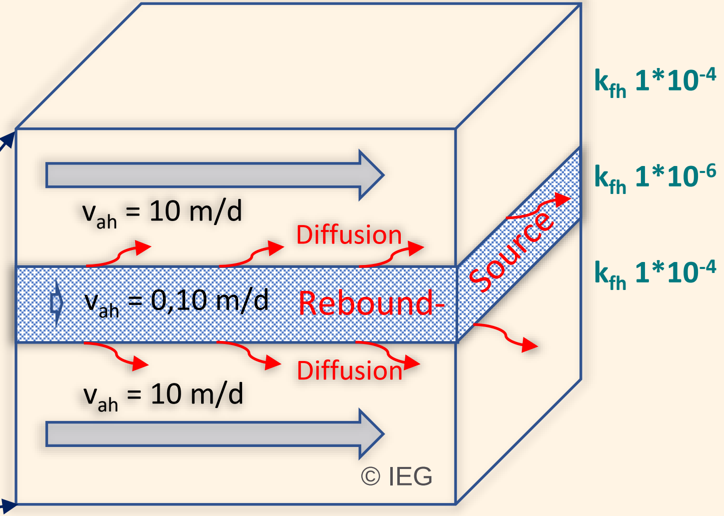
Fine sand or silt layers continue to deliver pollutants to neighbouring pore channels with higher flow over long time periods (rebound effect)

High-permeable sediment layers show only low pollution loads after several pore water exchanges

Example:

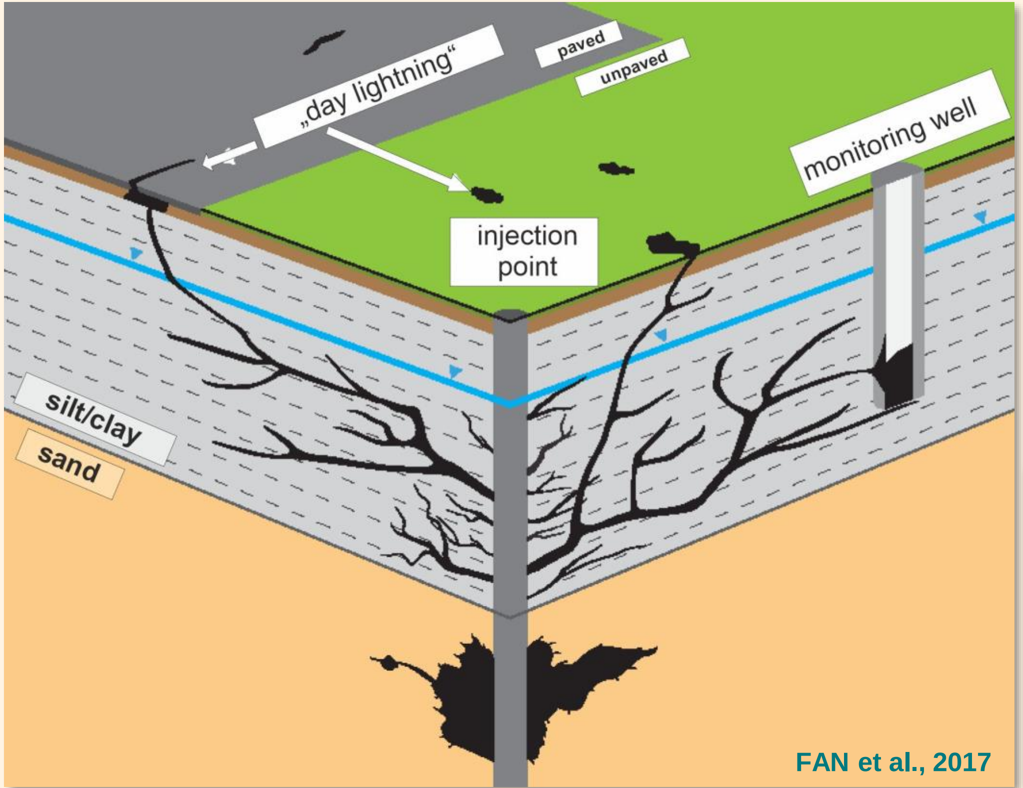
Aquifer with alternating sand and silty sand layers



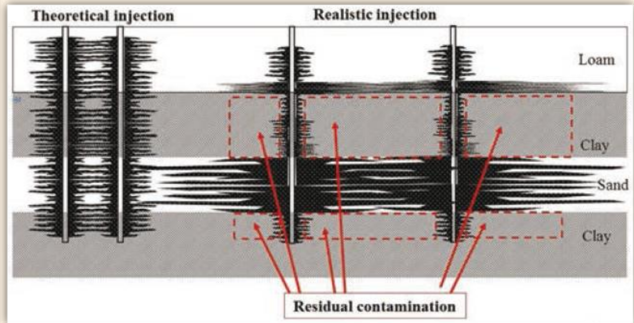


In layers with higher permeability, groundwater flows horizontally to the remediation well 100 times faster compared to fine-grained layers. As a result, the remediation process in heavily contaminated layers takes 100 times longer due to slower pore water exchange, extending the overall time required for remediation efforts.

Problems and difficulties



Examples of improper chemical injection practices



Recommendation:

Hydraulic control of vertical flow in aquifers

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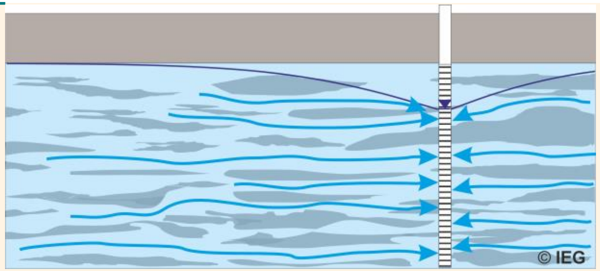
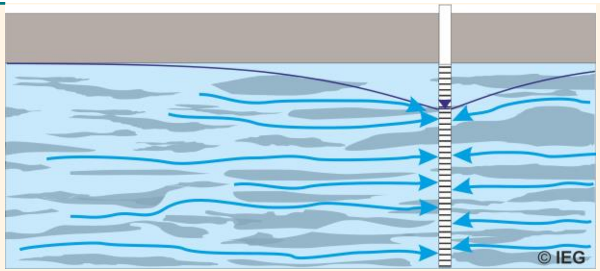
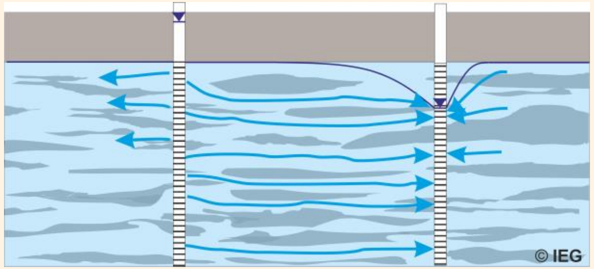


Horizontally bedded fine-grained structures impregnated with pollutants cannot be sufficiently hydraulically addressed using P&T

Recommendation: Hydraulic control of vertical flow in aquifers





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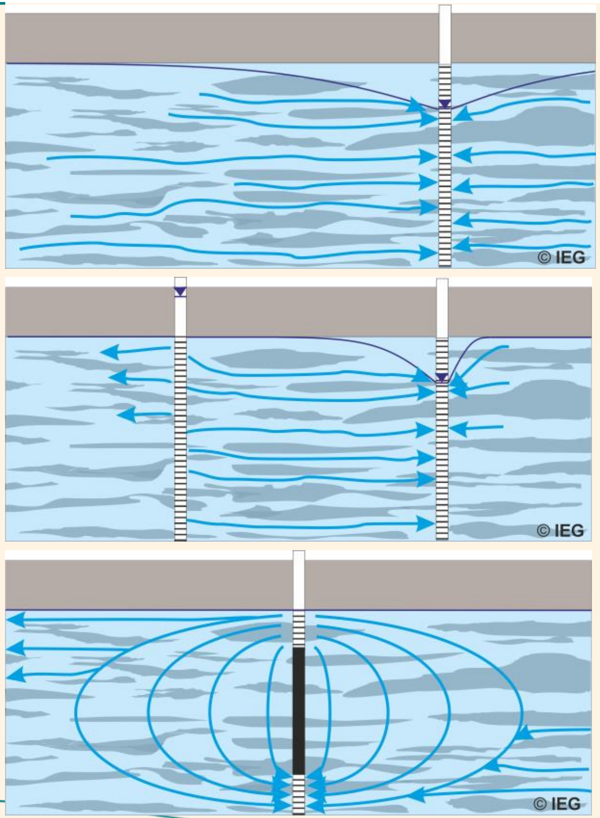

Horizontally bedded fine-grained structures impregnated with pollutants cannot be sufficiently hydraulically addressed using P&T

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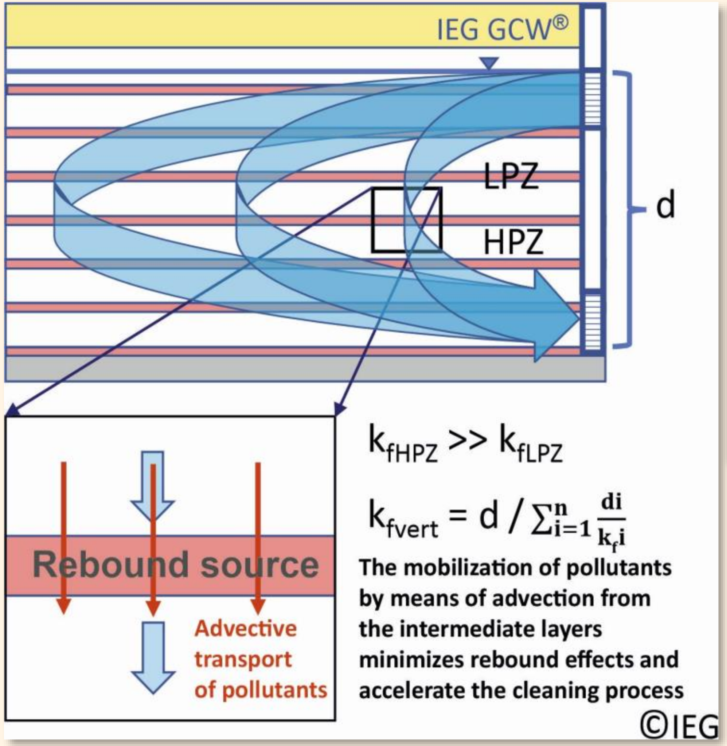
Such structures can only be hydraulically effective addressed by arranging extraction and infiltration sections in a vertical well axis

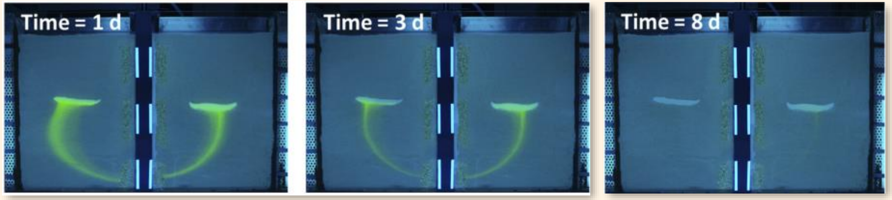
Recommendation: Hydraulic control of vertical flow in aquifers



LPZ: "low permeable zone"

HPZ: "high permeable zone"

Low permeable areas are surrounded by flow, yet a considerable hydraulic gradient (e.g. I = 1.0) exists between the top and bottom of an LPZ, resulting in forced flow through the structure.



TATTI et al., 2019

Advantages:

- No extraction of groundwater, conservation of natural resources
- When groundwater levels decrease infiltration above the groundwater table is possible (soil flushing circulation)
- Reversal of circulation direction, stacked circulation cells in a well axis
- Effective hydraulic addressing of pollutant sources (mobilization, injection of reagents, biosurfactants)
- Real-time readjustment (e.g. well hydraulics, reagent quantities)
- Low energy consumption (compared to P&T)
- **Cost savings due to shorter remediation times**

„A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.

(Max Planck, Autobiography 1948)

Thank you for your attention