Enhancement of LNAPL *in situ* recovery using soil washing with a surfactant solution

By:

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Presentation Objectives

(1) Present the facilities for Site Remediation at the INRS-ETE laboratory in Quebec City;

(2) Present our current research project: a **3D** lab-scale soil and groundwater remediation test using a technology train, including both Slurping and SEAR.

Project Background – *In Situ Limitations*

- Successful GW remediation requires almost total LNAPL mass reduction from source zone ;
- *In situ* technologies have mass-reduction limitations :
  - Slurping: leaves residual LNAPL trapped in the saturated zone by capillary forces;
  - SEAR: requires large volumes of solutions and effluent treatment is not economically interesting.

Project Background – *Recovery Mechanisms*

- SEAR targets 2 LNAPL recovery mechanisms:

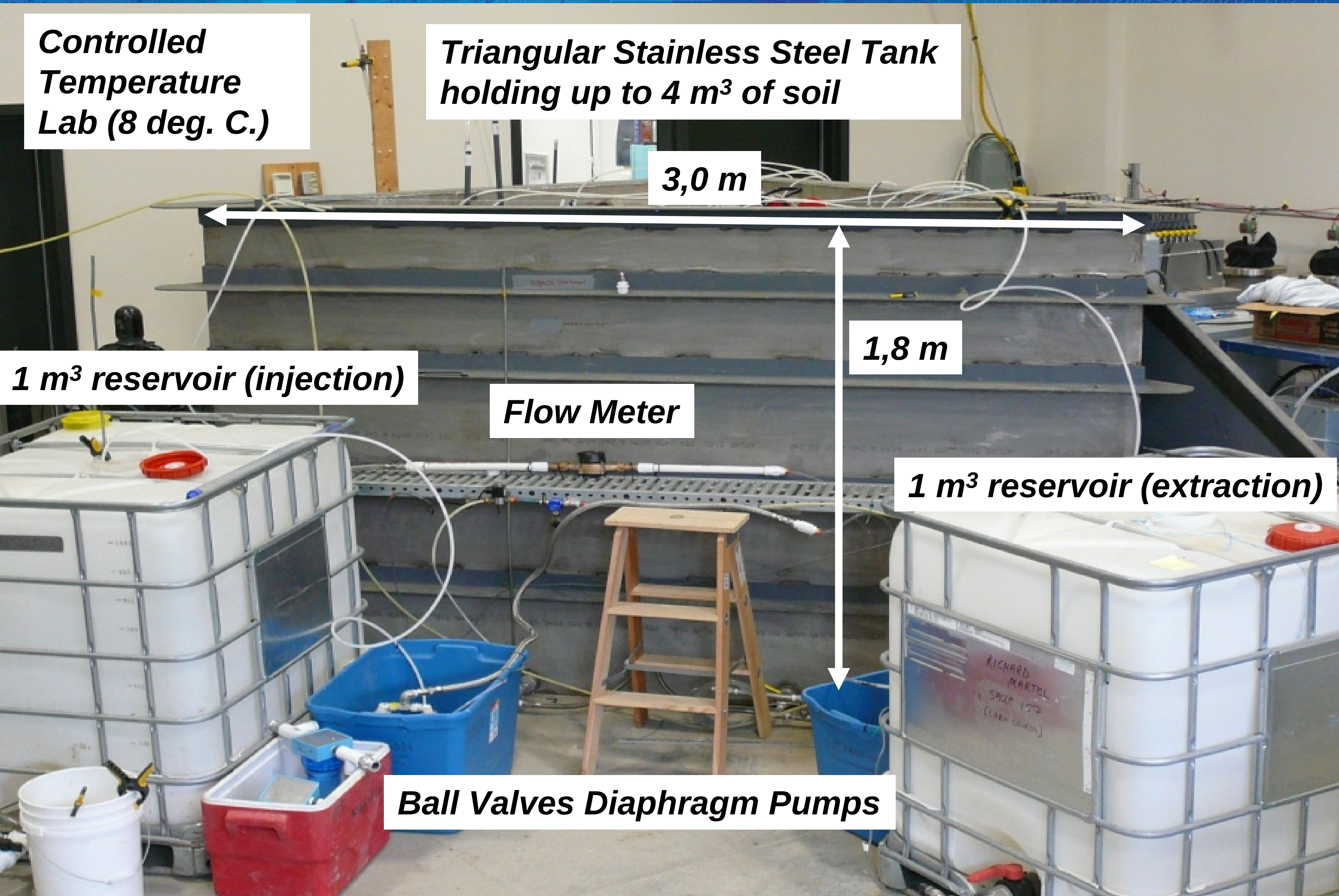
1) LNAPL mobilisation
   - Reduction in capillary forces;
   - Increase in oil relative permeability;

2) LNAPL increased dissolution in water
   - Micelle formation above the critical micelle concentration.

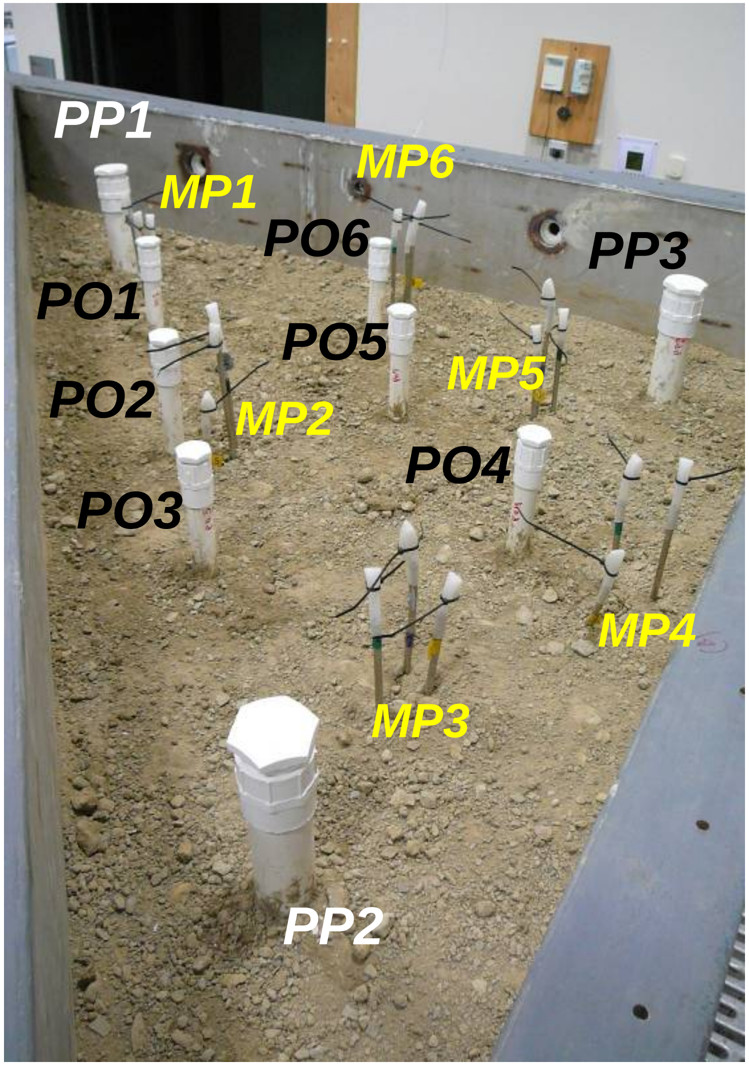
Project Background – *3D Lab. Experiments*

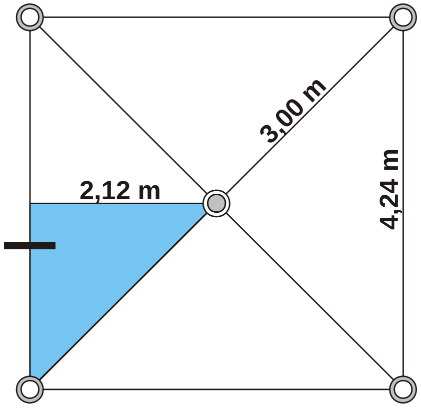
- 1D experiments are usually promising – but what is the performance in a 3D environment representing field conditions?
  - Actual field-like injection/extraction pattern with RADIAL FLOW;
  - Analysis of 3D phenomena:
    - Sweep efficiency (contact) and preferential flow effects on recovery
    - Dispersion in the soil and dilution at extraction wells
  - Field-characterisation tests can be performed inside the 3D model and results can be compared with actual field values:
    - Slug tests
    - Inter-well tracer tests

KEY PARAMETER FOR IN SITU SUCCESS!


Controlled Temperature Lab (8 deg. C.)
Triangular Stainless Steel Tank holding up to 4 m³ of soil
3,0 m
1,8 m
1 m³ reservoir (injection)
Flow Meter
1 m³ reservoir (extraction)
Ball Valves Diaphragm Pumps

Methodology- *Laboratory setup*





1/8 of a 5-spot pattern

1 Injection well: PP1

1 Extraction well: PP2

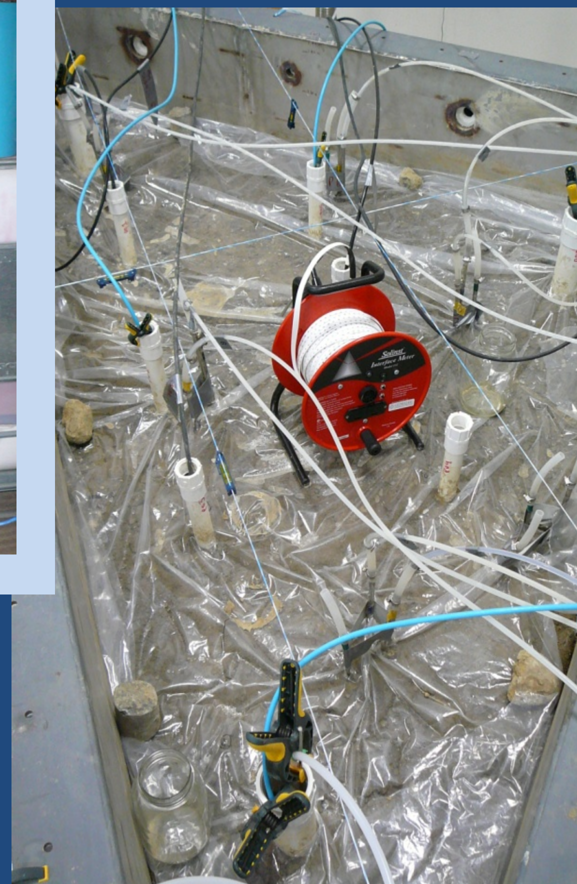
7 Observation wells: PO1 to PO6, PP3

6 Three-levels sampling wells:
MP1 to MP6

4 Pressure probes
PP1, PO1, PO3, PO5

4 Salinity probes
PO2, PO6, PP3, PP2

Slurping unit



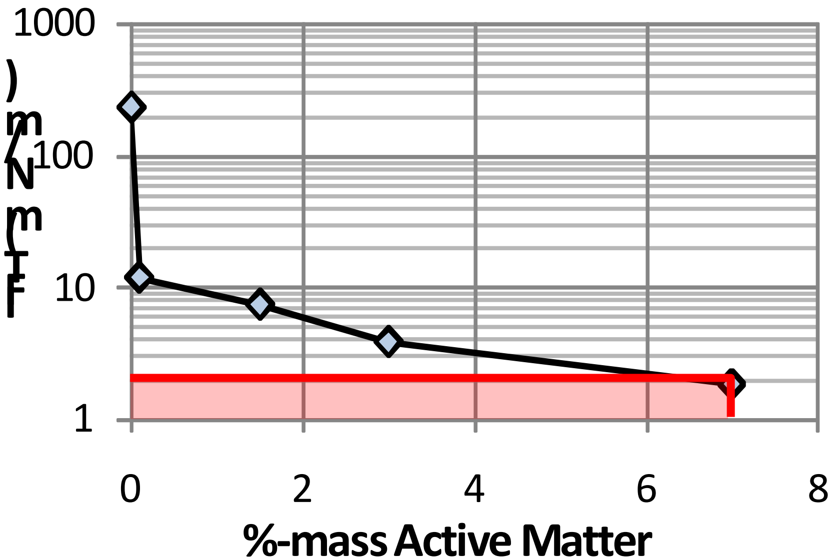
Water deaeration towers

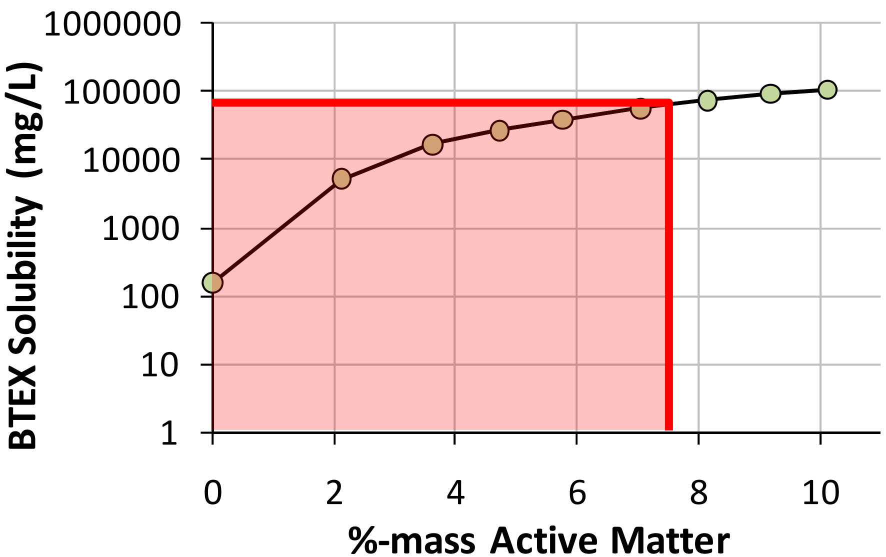
Data acquisition and operation control

Automatic water samplers

Methodology- Washing solution selection

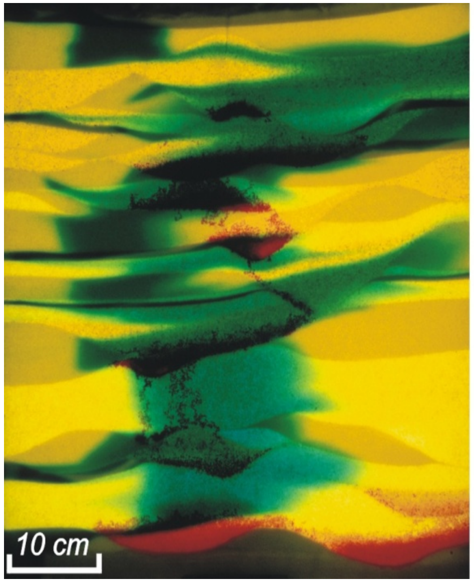
- Confidential blend (*Ionic surfactant* + *Co-solvent* + *Polymer* + *NaCl*)
- Injection concentration is over 60 X CMC (*Enhance LNAPL solubility)*
- Sand column experiments : 94%-mass removal of weathered gasoline after a 1,8 PV flush *(both mobilisation and solubilisation observed)*
- Potential impact on IFT and on BTEX dissolution:





Methodology- Washing solution selection

- Co-solvent (ex. alcohol):
  - Increases surfactant solubility in solution ;
  - Contributes to enhanced oil solubilisation ;
  - Contributes to *IFT* reduction.
- Shear-thinning polymer:
  - Stabilize the sweeping front (favourable mobility ratio) ;
  - Increase viscous forces.



Example of mobility control from a previous project (DNAPL) *From Robert et al. 2006*

Methodology- Overall experiment

1. Water saturation;
2. Water flood for tank conditioning (pH, EC, ORP, T)
3. Tank drainage (down to 0,5 m elevation)
4. Model oil injection through all wells present in the tank (up to 1 m elevation)
5. Water flood in order to reach an equilibrium: Remove excess oil in tank
6. Remediation :
   - Slurping
   - Salinity conditionning
   - Micellar flood
   - Micellar+ polymer flood
   - Polymer Flood
7. ISCO (to be planned)

Results- Sand Tank Physical Characteristics

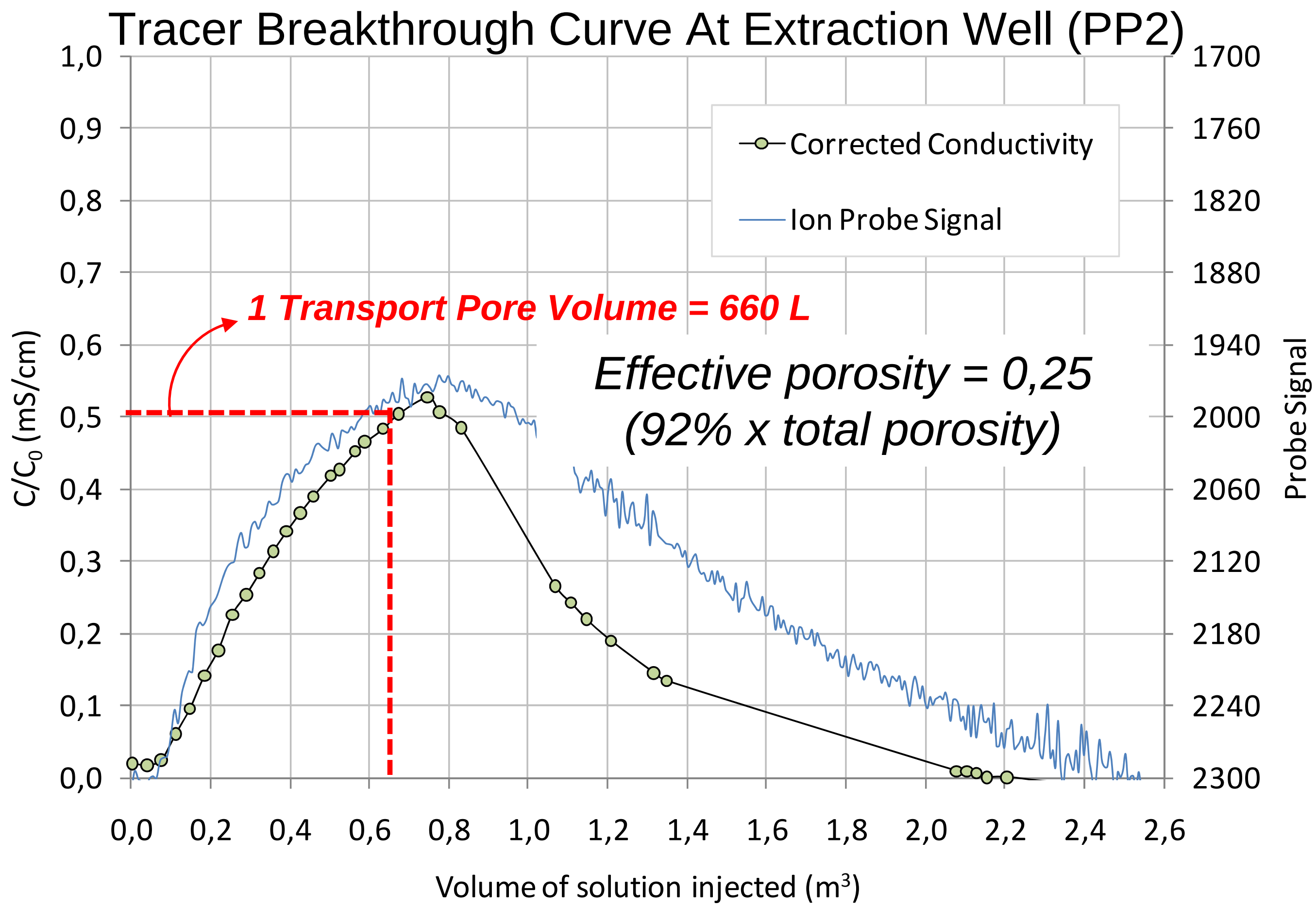
Parameter	Unit	Value
Soil Surface Area	m^2	2,3
Soil Thickness	m	1,5
Volume of Soil	m^3	3,3
Mass of Soil	Kg	6540
Dry Soil Density	Kg/m^3	1980
Total Soil Porosity	-	0,27
Pore Volume	L/saturated m	620
d_{50}	1,5 mm (medium sand)	
d_{10}	0,1 mm	
Mineralogy	Mainly Quartz (dominant) + Calcite	

Results- Saturated Zone Properties

- Soil hydraulic conductivity: 2×10^{-5} m/s to 8×10^{-5} m/s (slug tests)

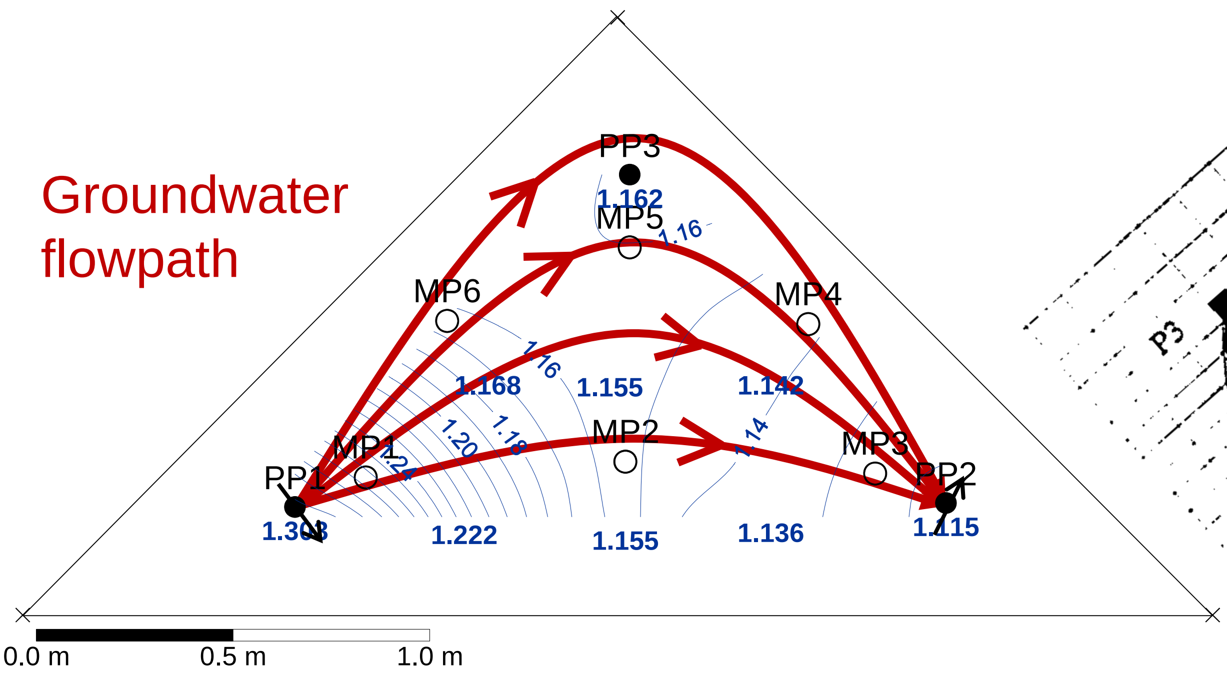
- Tracer test (prior to contamination):

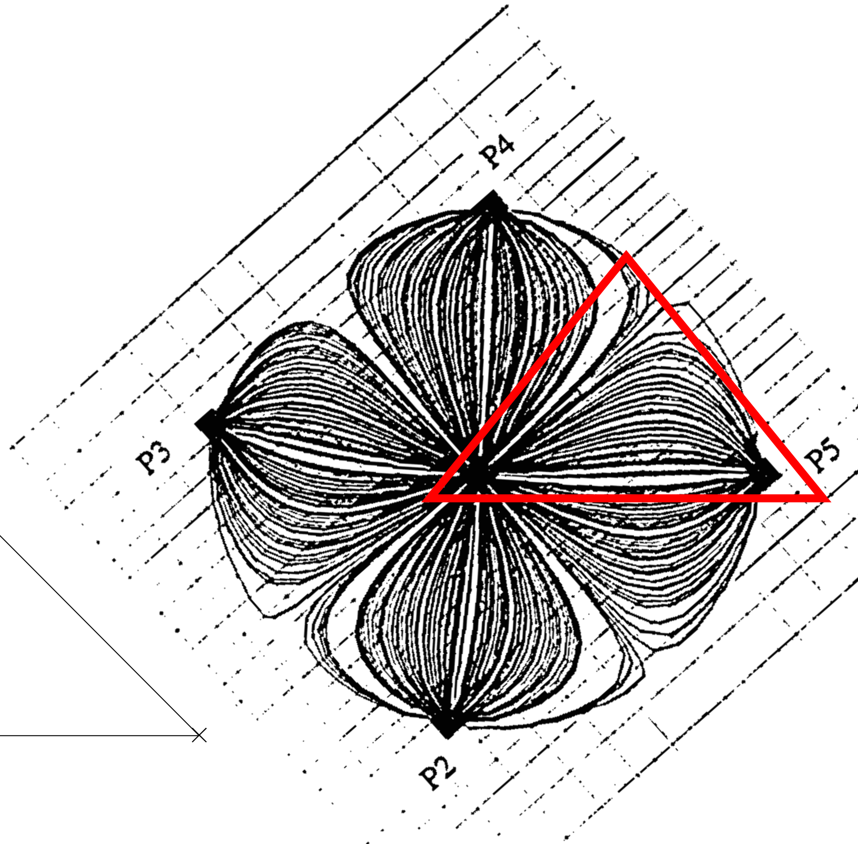
0,7 m³ injected @ [Cl⁻] = 1000 mg/L, followed by 1,9 m3 of water



Results- Saturated Zone Properties

- Water elevations and piezometric map under stable conditions (steady-state, $Q_{injection} = Q_{extraction}$, dh = 0,2 m)



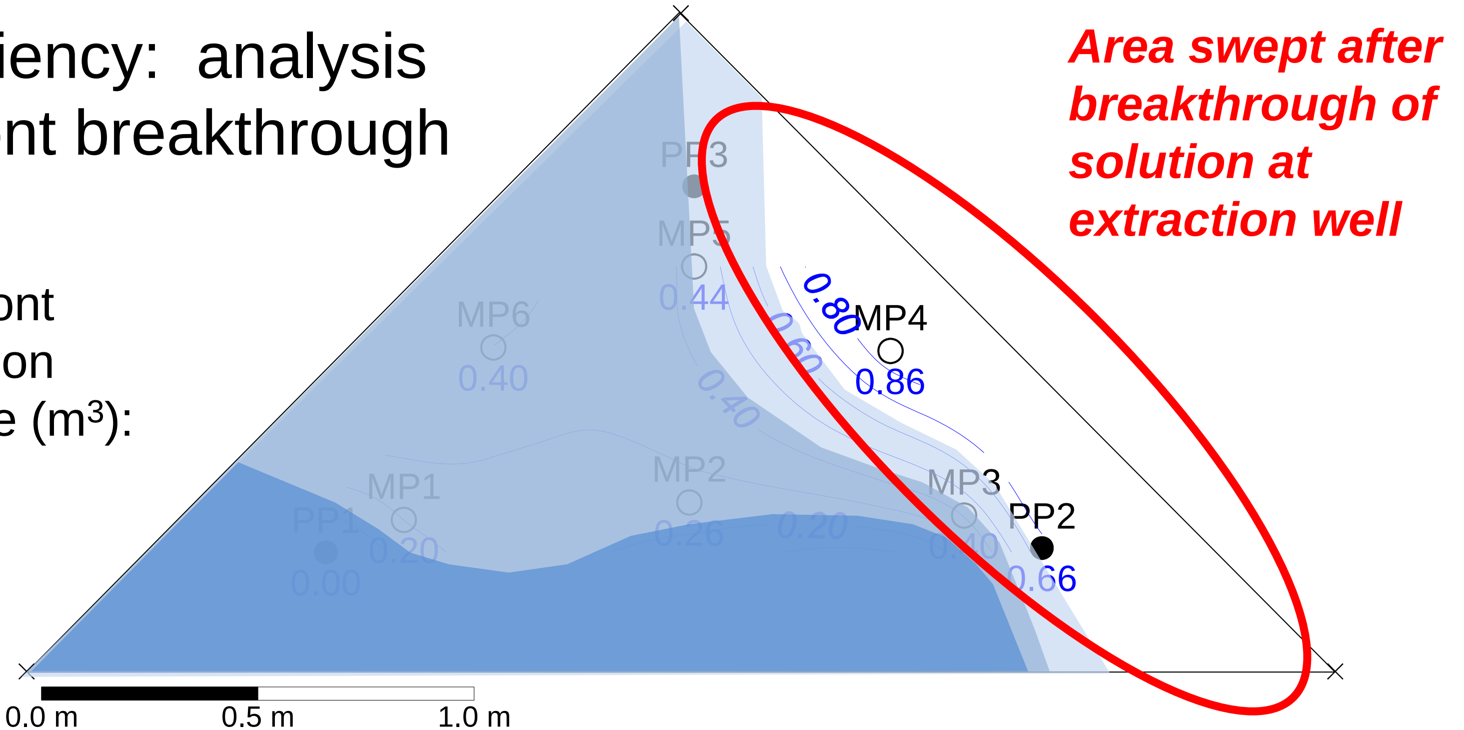


Results- Saturated Zone Properties

- Sweep efficiency: analysis of tracer front breakthrough

Arrival of tracer front at MPs as a function of injection volume (m^3):

Mil-level screens (0,6 m elevation)



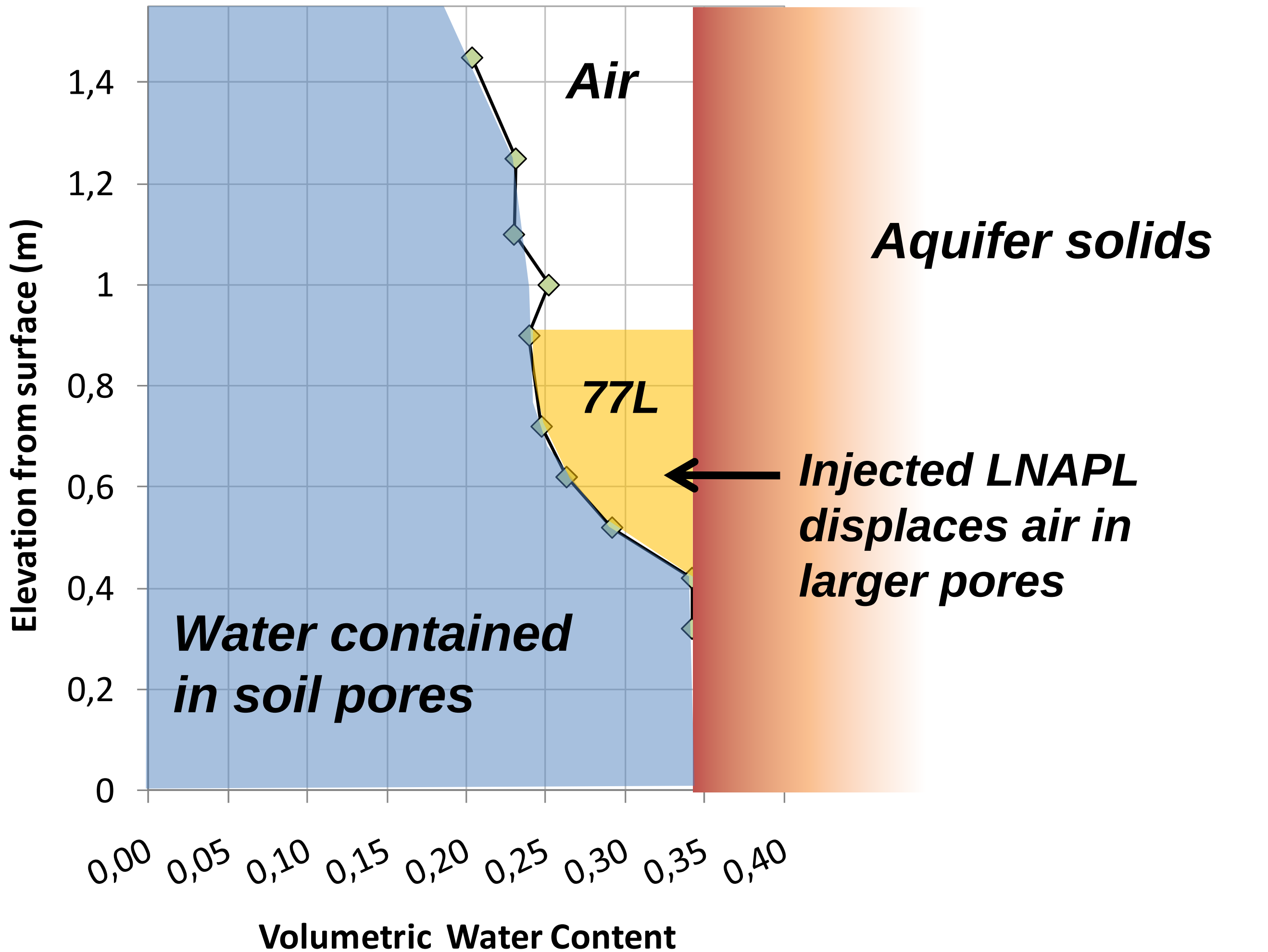
After injection of 220L (1/3 transport PV)

440L (2/3 transport PV)

660L (1 transport PV)

Results- Unsaturated Zone Properties

- Volumetric water content profile:



Results- LNAPL recovery by Slurping

- Operation parameters:

Parameter	Unit	Value
Vacuum Pressure at Extraction Well	(cm water)	-25
Vacuum Pressure at Pump	(inch Hg)	-22
Air Extraction Flow Rate	(m3/hr)	9,3
	(scfm)	5,5
Total Operation Time	(hrs)	4 X 8 hrs
Volume of Water Injected During Operation	(L)	670 (1 transport VP)

Results- LNAPL recovery by Slurping

- Slurping performance assessment:

Parameter		Unit	Value
LNAPL Volume in Soil	Initial	(L)	44
	Final	(L)	27
Total Volume Removed		(L)	17 (39% reduction)
LNAPL thickness in wells	Initial	(cm)	24
	Final	(cm)	1,6
Oil Saturation	Initial	(%)	14
	Final	(%)	9

Results- SEAR

- Operation parameters:

Parameter		Unit	Value
Injection Rate		(L/min)	0,24
Injected Volume	Water + NaCl	(L)	560
	Micellar Solution	(L)	310
	Micellar + Polymer Solution	(L)	310
	Polymer Solution	(L)	760
	Total	(L)	1940
		(days)	6

Results- SEAR

- Samples collected at extraction pump (PP2)
- LNAPL recovery mechanisms observed at extraction well (PP2):
  - Some mobilization ahead of the surfactant solution front ;
  - Enhanced solubilization is the main recovery mechanism.

NaCl

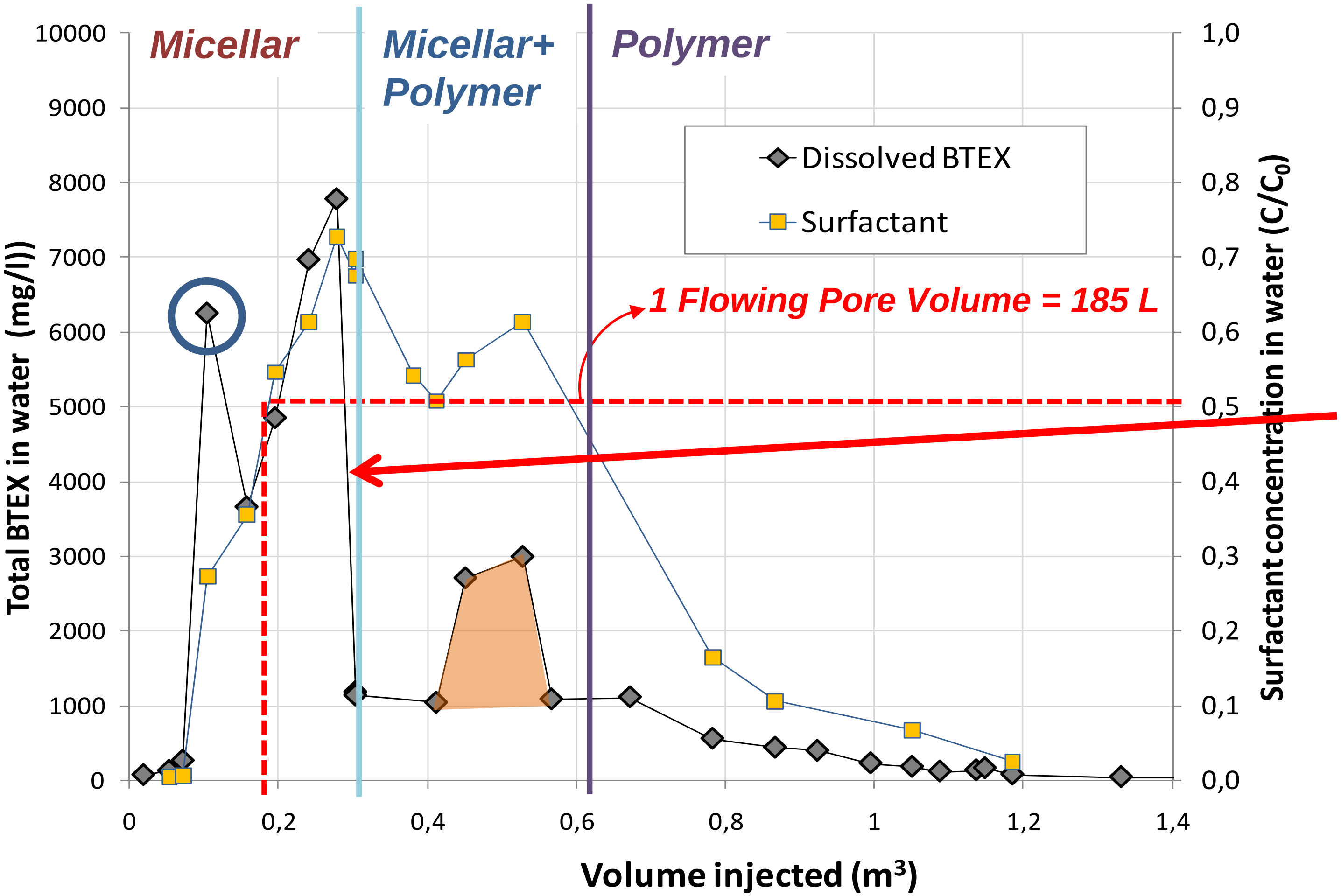
Micellar Solution

Micellar + Polymer Solution

Polymer Solution

Results- SEAR

- BTEX and surfactant concentration at extraction well (PP2):



Mobilisation

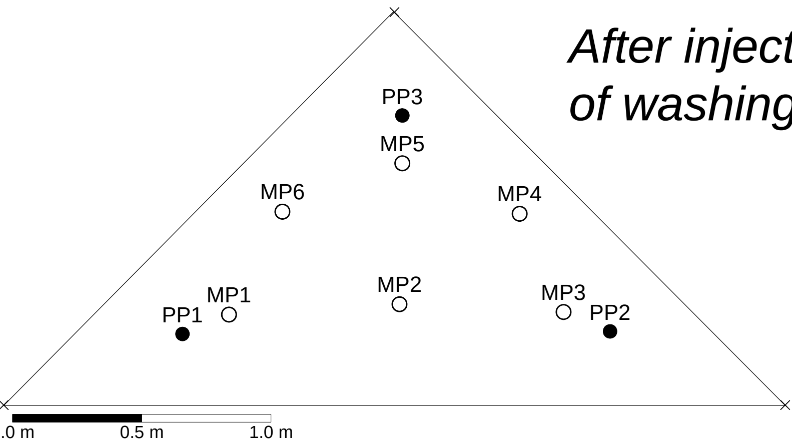
Eff. Porosity = 0,11 (40% x total porosity): Oil saturation caused A 50% decrease in eff. porosity

[BTEX] drops rapidly behind the Micellar Solution Front: Preferential flow and dilution (underiding of washing solution)

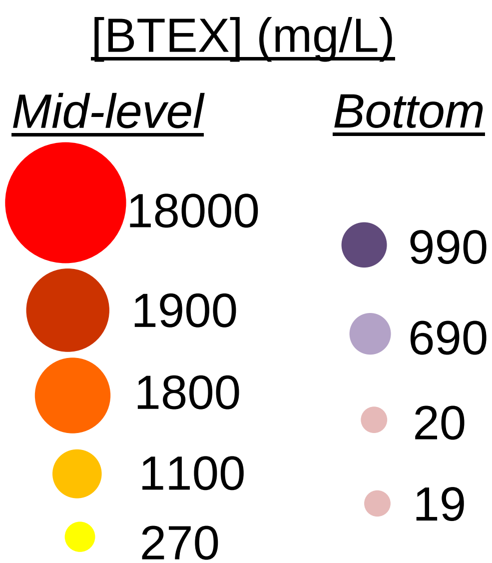
Impact of polymer-induced mobility control

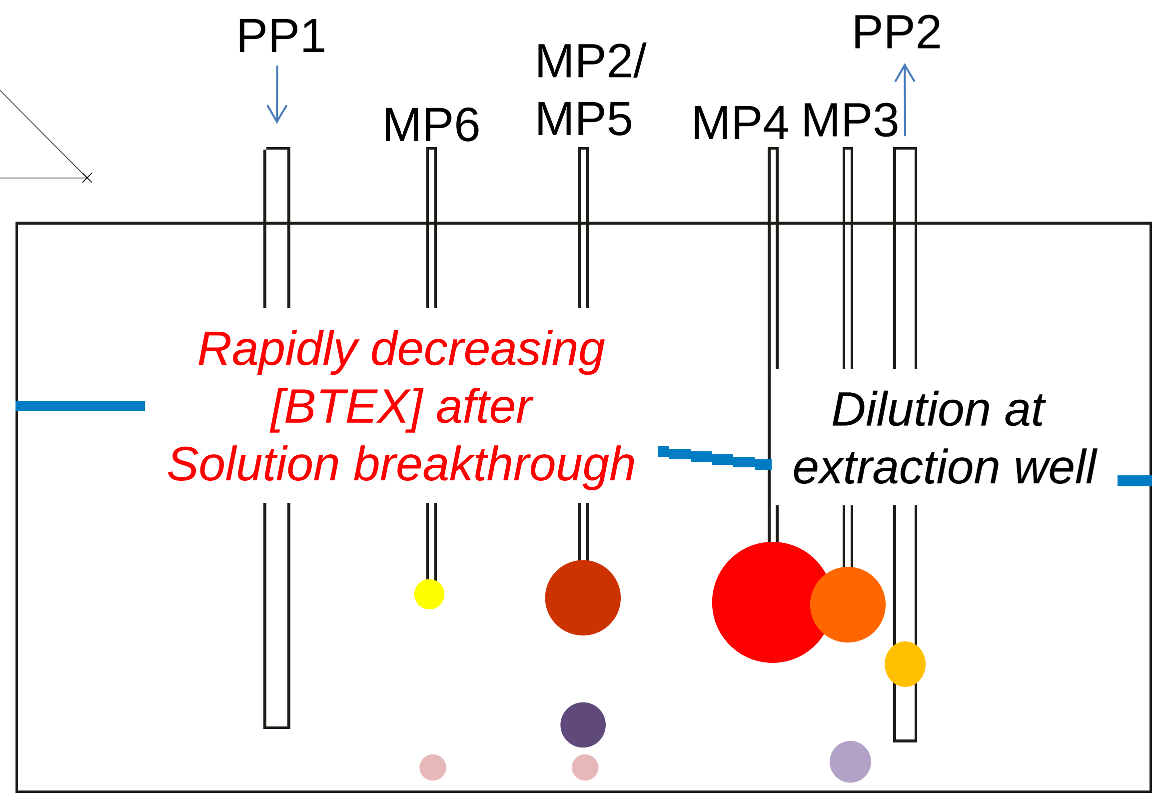
Results- SEAR: [BTEX] inside the tank

After injection of 300 L of washing solution



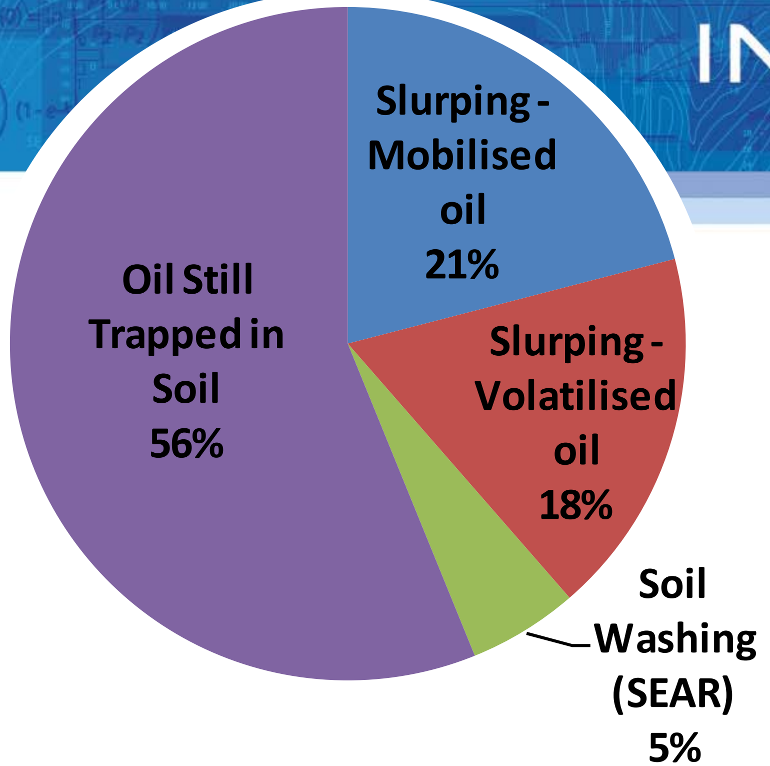
Preferential flow and dilution (underiding of washing solution)





Conclusions

- Overall recovery:



- Impact of remediation on soil concentrations:
  – Bioslurping: 3500 mg/kg reduction
  – Soil washing: 350 mg/kg reduction
- No significant impact on dissolved flux exiting the treatment area

Conclusions - SEAR

- Seep efficiency was not uniform inside the tank:
  - Effective porosity globally dropped by 50% after oil injection;
  - Dissolution not uniform behind micellar solution front;
  - Preferential flow and under-rinding is suspected (**3D effects**).
- A total of 2 kg of BTEX was removed by dissolution
  - Equivalent to a 350 mg/kg BTEX reduction in soils

Conclusions

- Pros of laboratory tests in large sand tanks:
  - True test prior to field since 3D effects have a huge impact on remediation performance
    - 1D test (column experiment) overestimated the performance
  - Experimental control over data
    - Mass balance was acheived
  - Reduced costs vs. field pilot study, allows optimisation process
- Room for improvement – other tank tests are planned!

Thank you!

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