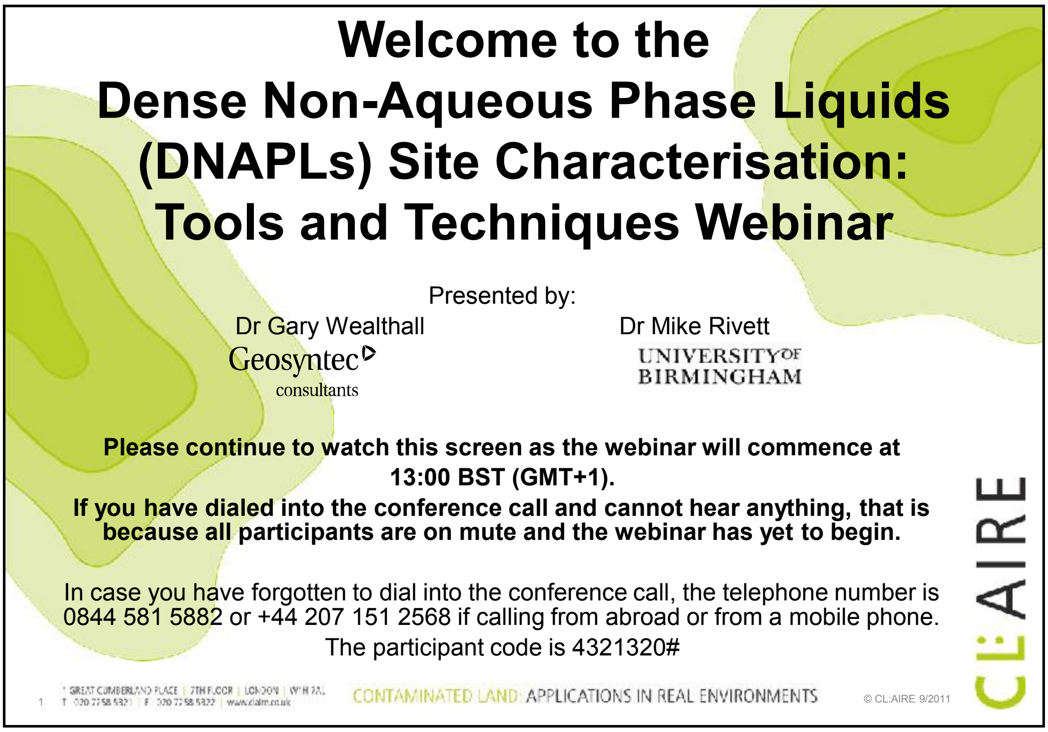

Welcome to the Dense Non-Aqueous Phase Liquids (DNAPLs) Site Characterisation: Tools and Techniques Webinar

Presented by:

Dr Gary Wealthall
Geosyntec consultants

Dr Mike Rivett
UNIVERSITY OF BIRMINGHAM

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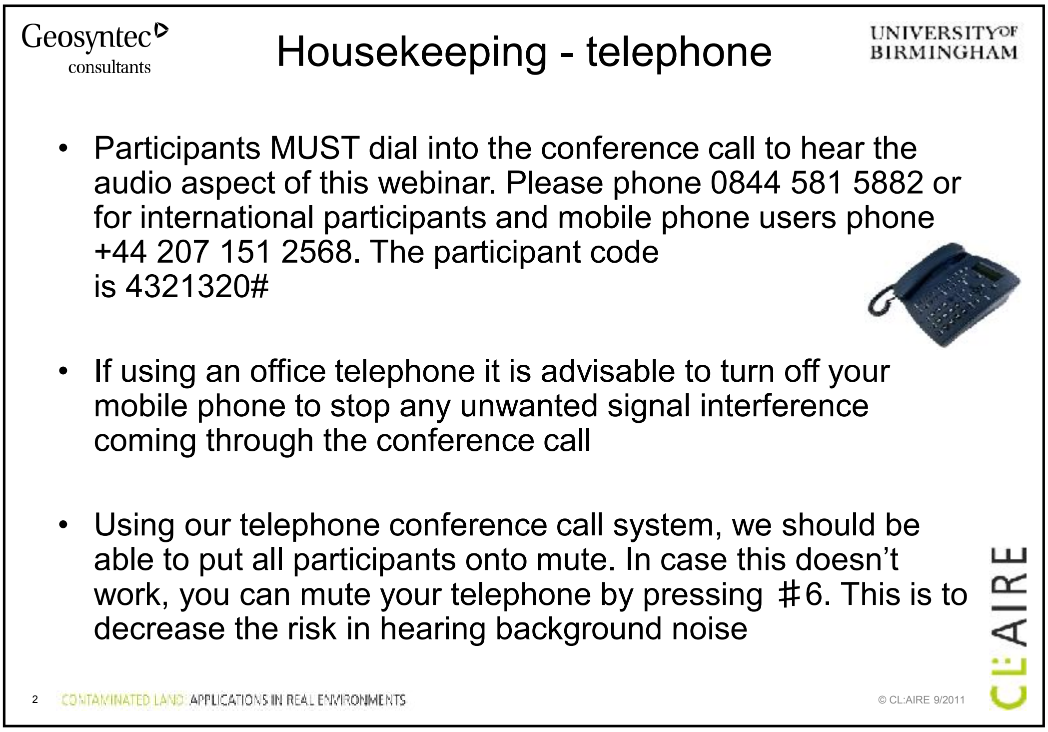

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Housekeeping – raising your hand

(technical problems)

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Welcome to
The SuRF-UK Framework for Assessing the Sustainability of Soil and Groundwater Remediation

Presented by:
Jonathan Smith, Shell Global Solutions (UK)
Paul Bardos, r³ environmental technology Ltd

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Welcome to
The SuRF-UK Framework for Assessing the Sustainability of Soil and Groundwater Remediation

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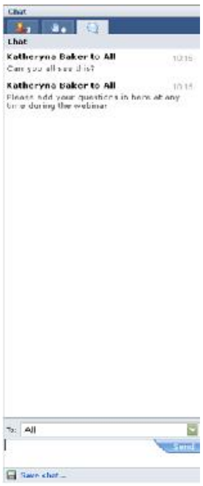

Katheryna Baker to All 10:15
Can you all see this?

Katheryna Baker to All 10:15
Please add your questions in here at any time during the webinar

To: All

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DNAPL Site Characterisation:

Tools and Techniques

22 September 2011

Gary Wealthall (Geosyntec Consultants, Inc)
gwealthall@geosyntec.com

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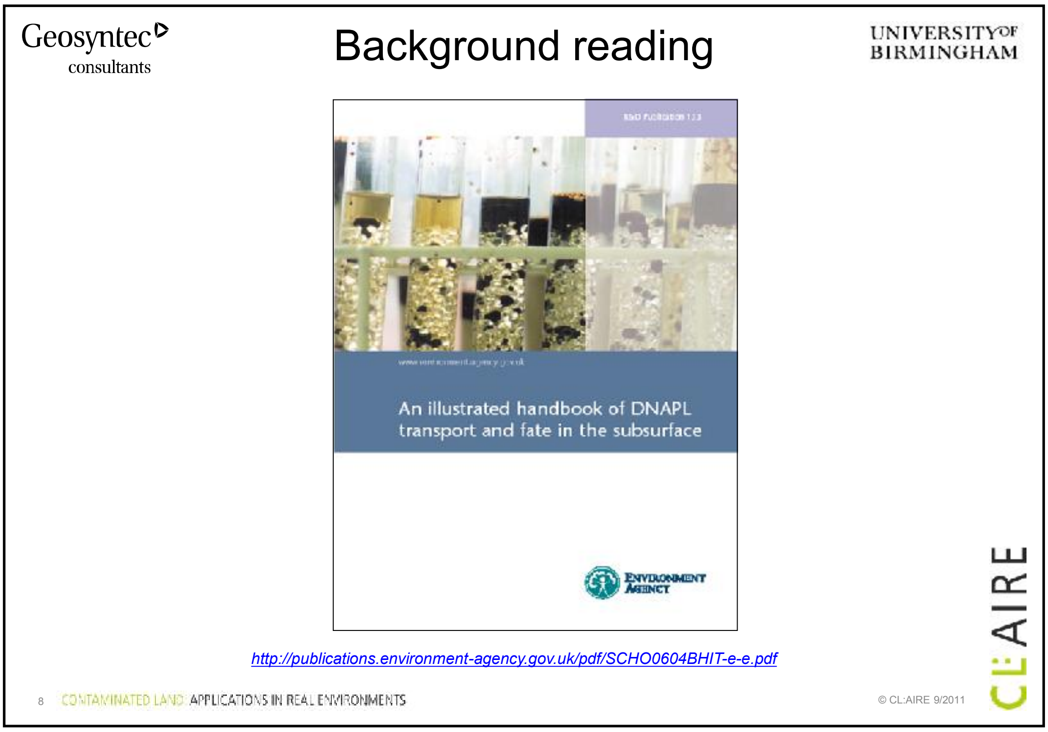

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Background reading

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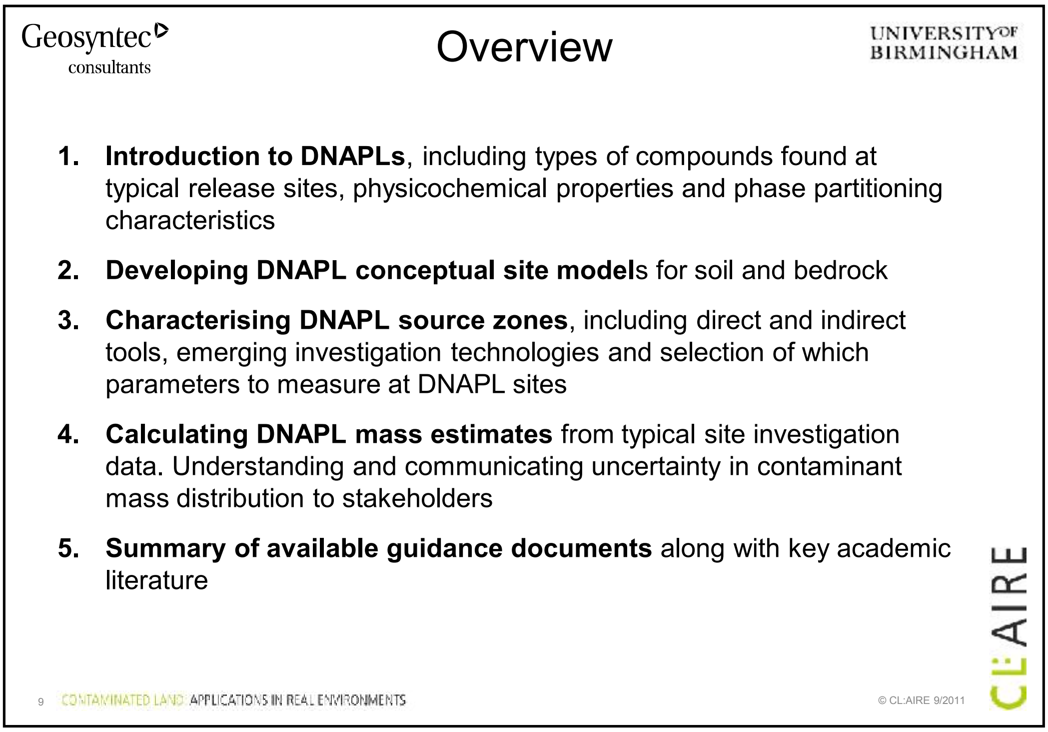
An illustrated handbook of DNAPL transport and fate in the subsurface

http://publications.environment-agency.gov.uk/pdf/SCHO0604BHIT-e-e.pdf



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Overview

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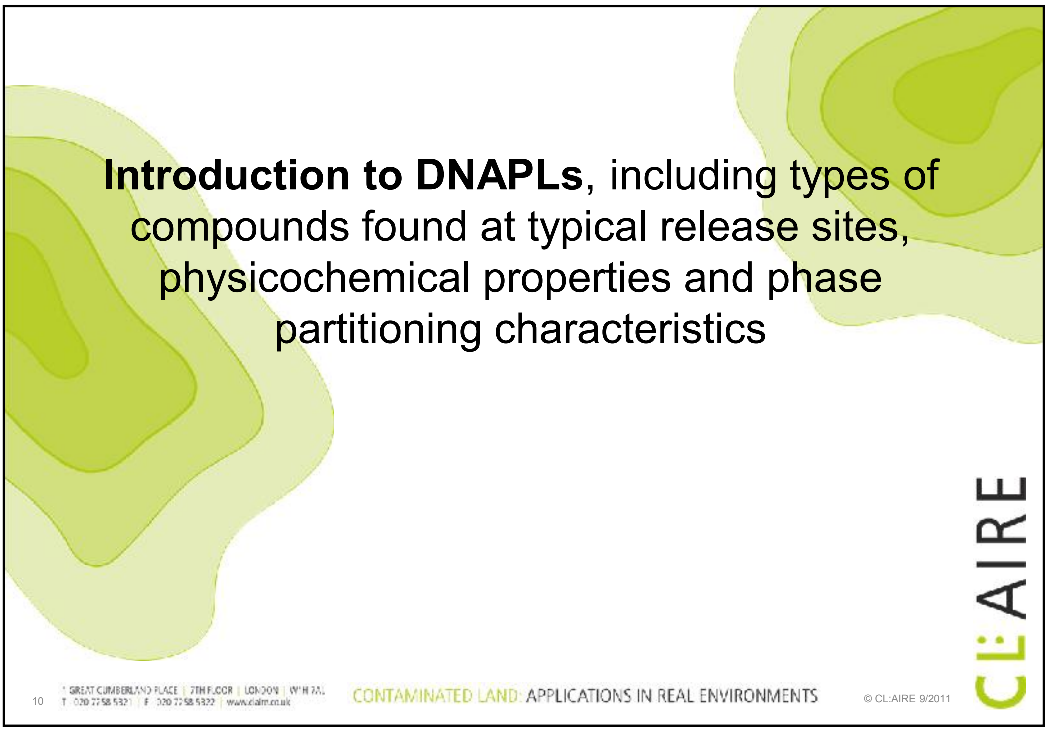
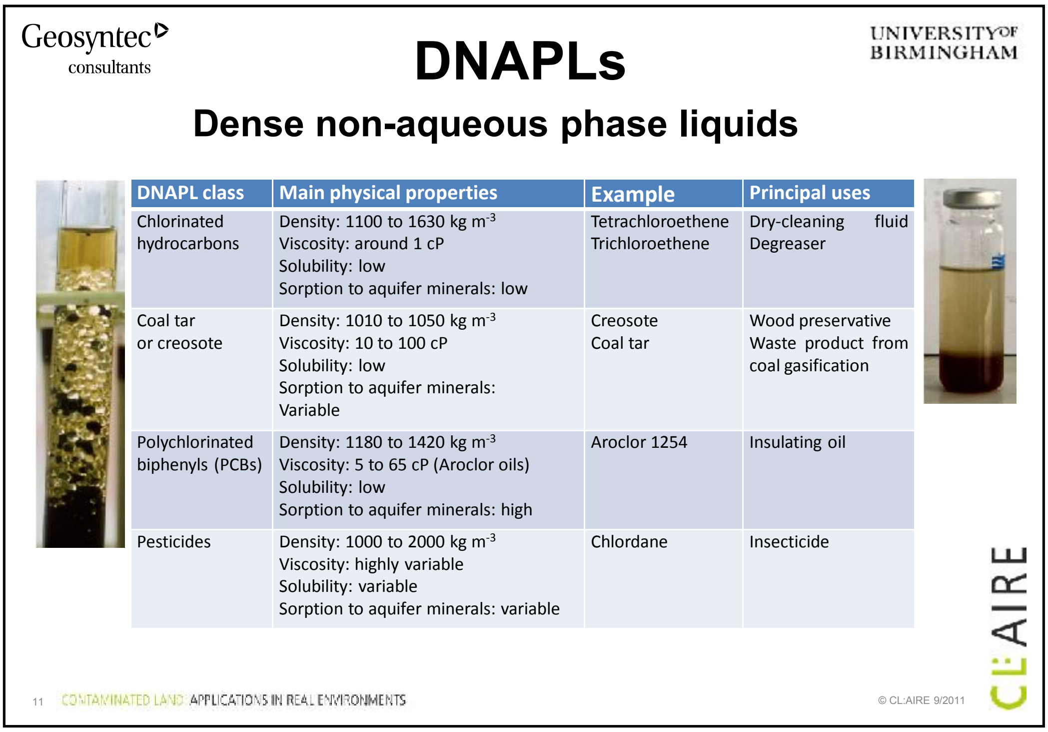
1. **Introduction to DNAPLs**, including types of compounds found at typical release sites, physicochemical properties and phase partitioning characteristics
2. **Developing DNAPL conceptual site model**s for soil and bedrock
3. **Characterising DNAPL source zones**, including direct and indirect tools, emerging investigation technologies and selection of which parameters to measure at DNAPL sites
4. **Calculating DNAPL mass estimates** from typical site investigation data. Understanding and communicating uncertainty in contaminant mass distribution to stakeholders
5. **Summary of available guidance documents** along with key academic literature



Introduction to DNAPLs, including types of compounds found at typical release sites, physicochemical properties and phase partitioning characteristics



DNAPLs

Dense non-aqueous phase liquids

DNAPL class	Main physical properties	Example	Principal uses
Chlorinated hydrocarbons	Density: 1100 to 1630 kg m^{-3} Viscosity: around 1 cP Solubility: low Sorption to aquifer minerals: low	Tetrachloroethene Trichloroethene	Dry-cleaning fluid Degreaser
Coal tar or creosote	Density: 1010 to 1050 kg m^{-3} Viscosity: 10 to 100 cP Solubility: low Sorption to aquifer minerals: Variable	Creosote Coal tar	Wood preservative Waste product from coal gasification
Polychlorinated biphenyls (PCBs)	Density: 1180 to 1420 kg m^{-3} Viscosity: 5 to 65 cP (Aroclor oils) Solubility: low Sorption to aquifer minerals: high	Aroclor 1254	Insulating oil
Pesticides	Density: 1000 to 2000 kg m^{-3} Viscosity: highly variable Solubility: variable Sorption to aquifer minerals: variable	Chlordane	Insecticide

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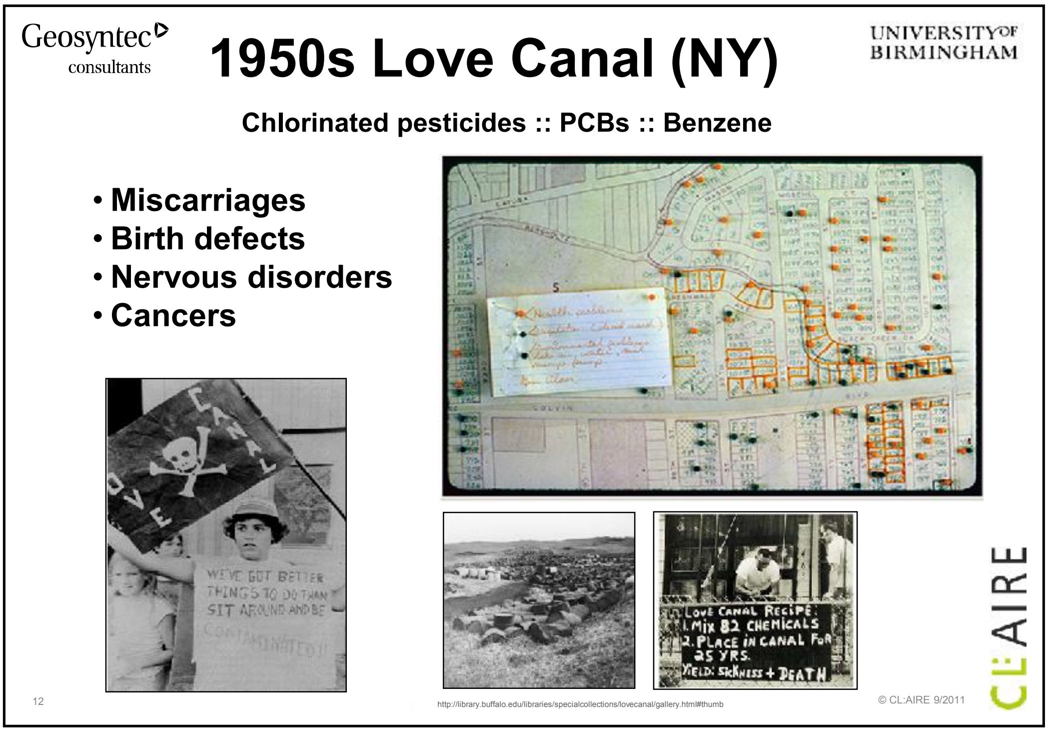
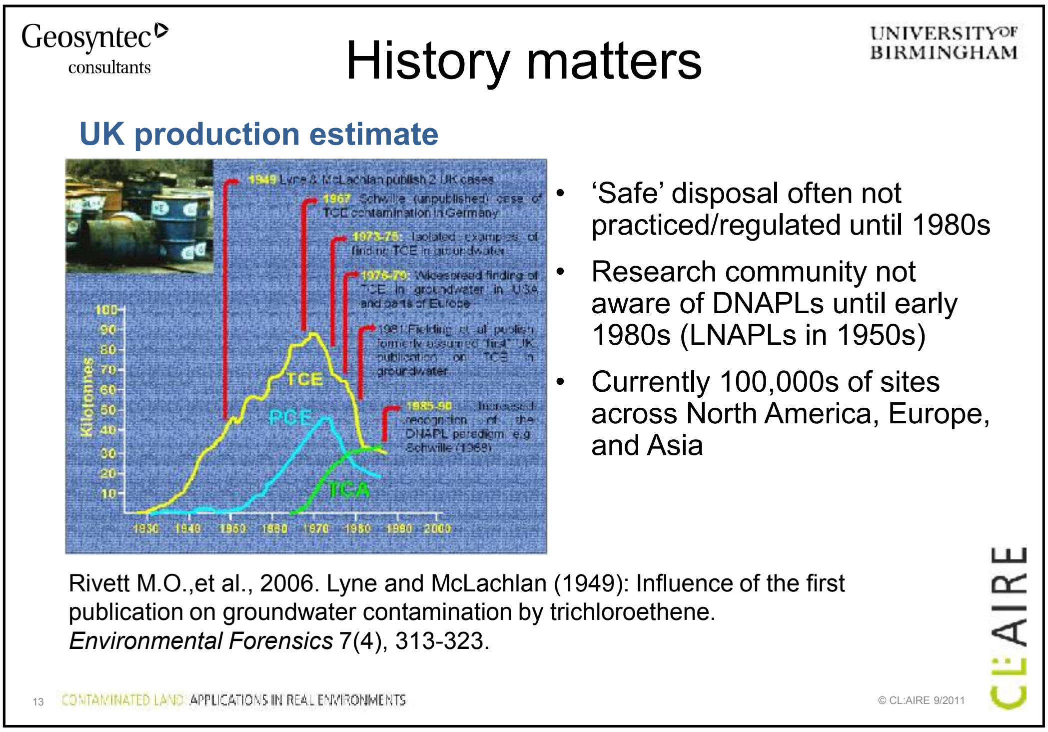


1950s Love Canal (NY)

Chlorinated pesticides :: PCBs :: Benzene

- Miscarriages
- Birth defects
- Nervous disorders
- Cancers

12 http://library.buffalo.edu/libraries/specialcollections/lovecanal/gallery.html#thumb © CL:AIRE 9/2011



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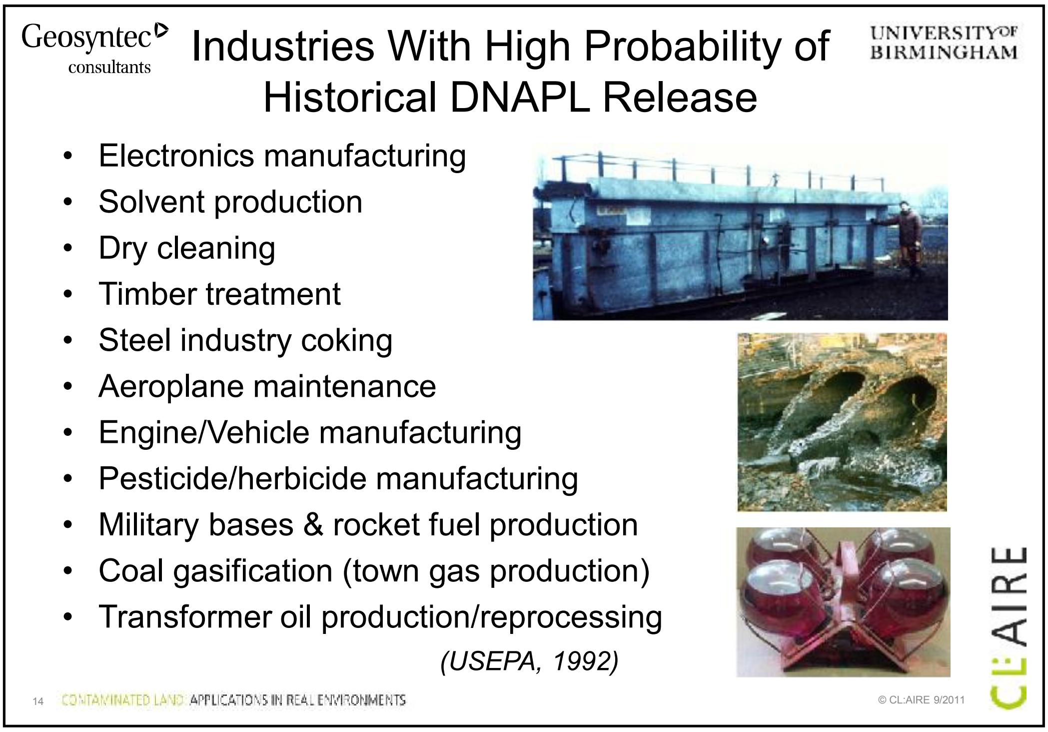
History matters

UK production estimate

- 'Safe' disposal often not practiced/regulated until 1980s
- Research community not aware of DNAPLs until early 1980s (LNAPLs in 1950s)
- Currently 100,000s of sites across North America, Europe, and Asia

Rivett M.O.,et al., 2006. Lyne and McLachlan (1949): Influence of the first publication on groundwater contamination by trichloroethene. *Environmental Forensics* 7(4), 313-323.



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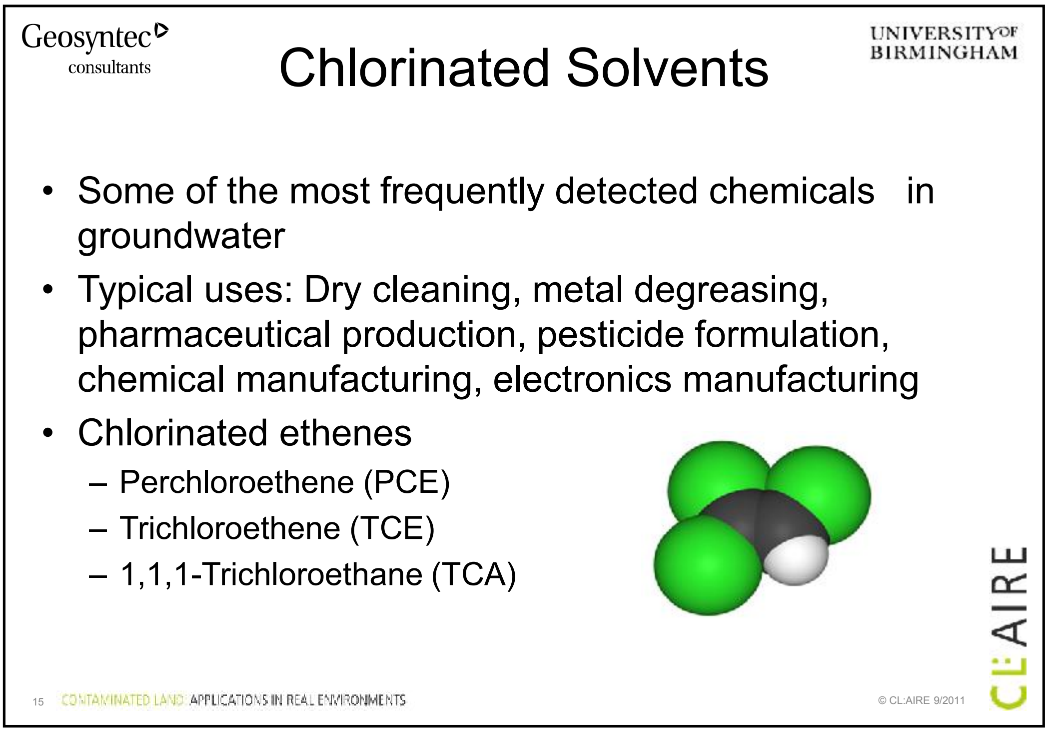
Industries With High Probability of Historical DNAPL Release

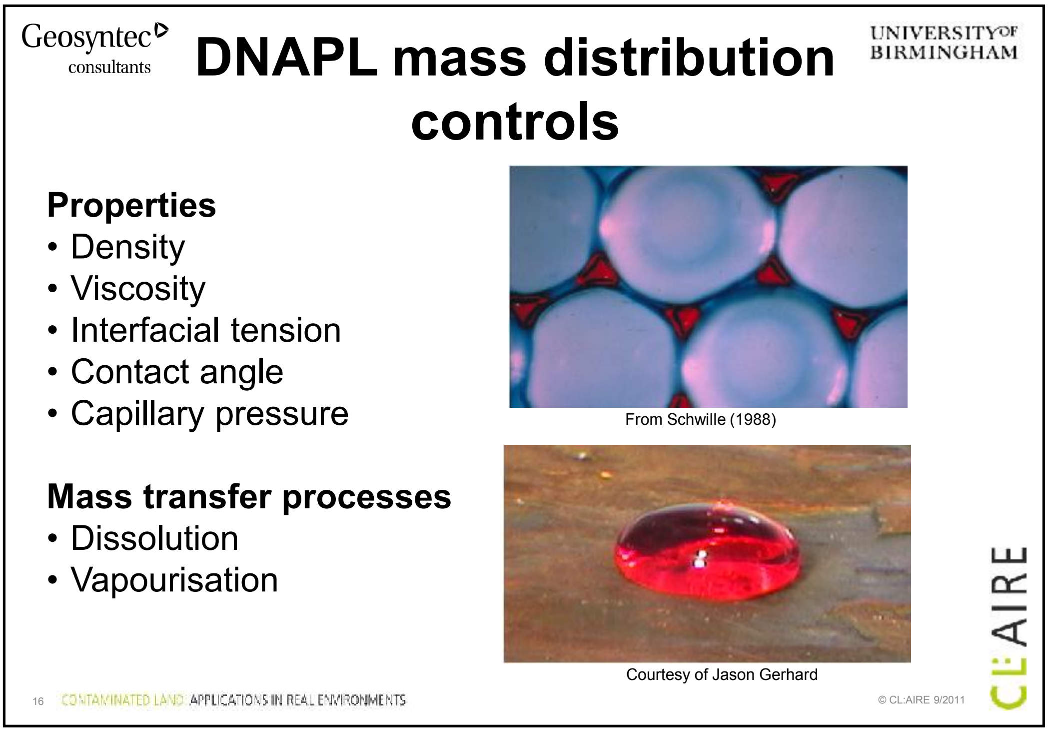
- Electronics manufacturing
- Solvent production
- Dry cleaning
- Timber treatment
- Steel industry coking
- Aeroplane maintenance
- Engine/Vehicle manufacturing
- Pesticide/herbicide manufacturing
- Military bases & rocket fuel production
- Coal gasification (town gas production)
- Transformer oil production/reprocessing

(USEPA, 1992)



Chlorinated Solvents

- Some of the most frequently detected chemicals in groundwater
- Typical uses: Dry cleaning, metal degreasing, pharmaceutical production, pesticide formulation, chemical manufacturing, electronics manufacturing
- Chlorinated ethenes
  - Perchloroethene (PCE)
  - Trichloroethene (TCE)
  - 1,1,1-Trichloroethane (TCA)



DNAPL mass distribution controls

Properties
- Density
- Viscosity
- Interfacial tension
- Contact angle
- Capillary pressure

Mass transfer processes
- Dissolution
- Vapourisation

From Schwille (1988)

Courtesy of Jason Gerhard

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DNAPL threshold entry values

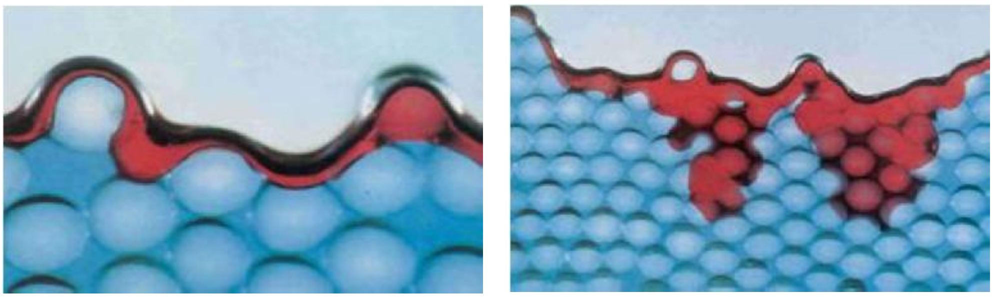
$$P_c = \frac{2\sigma Cos\,\phi}{e}$$

Interfacial tension

Contact angle

Capillary pressure

Fracture aperture or pore throat dimension



no invasion ⟹ P_c > entry pressure ⟹ invasion

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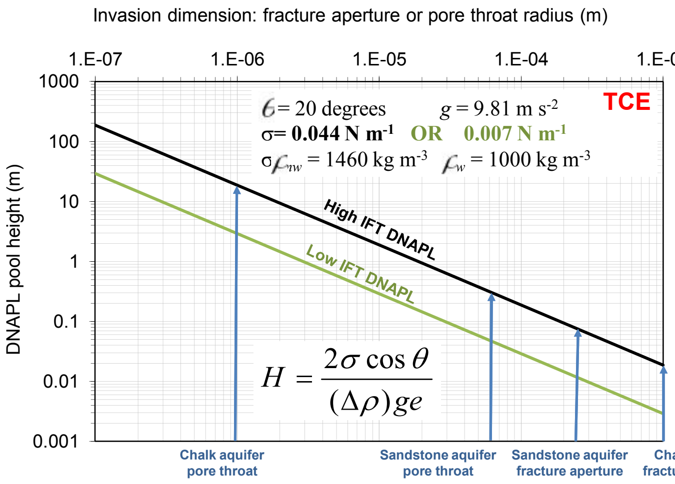
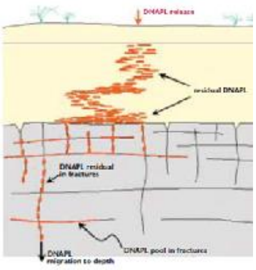
DNAPL entry pressure for fractures and matrix





DNAPL Handbook

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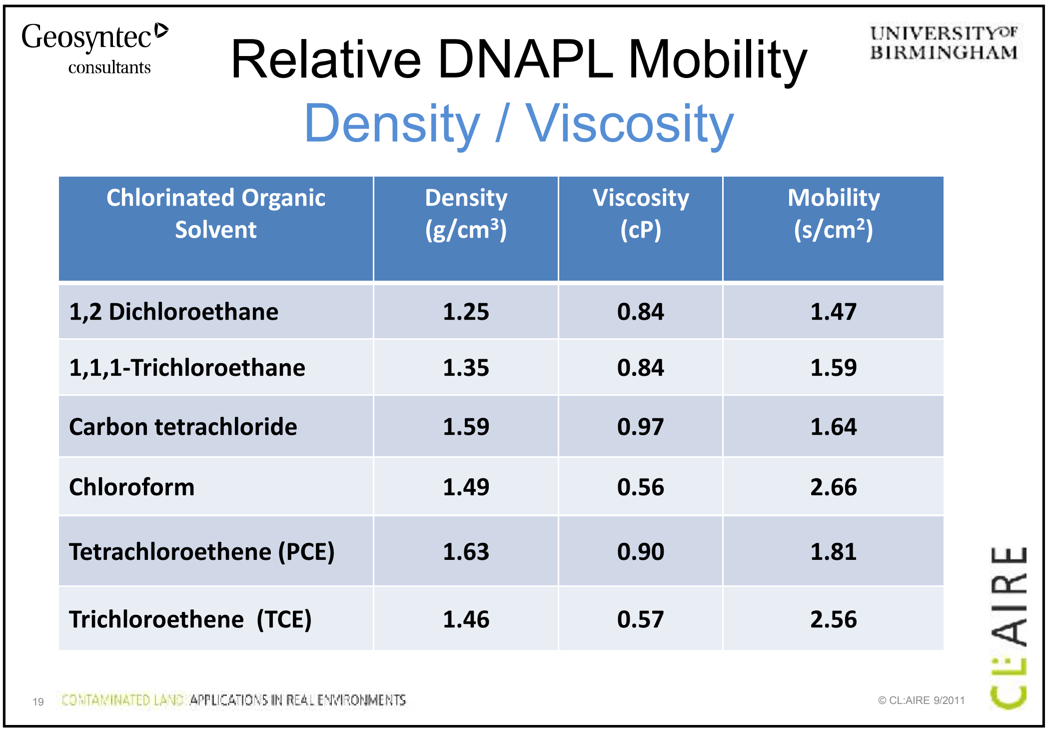
Presented by:
Dr Gary Wealthall, Geosyntec Consultants Inc. and Dr Mike Rivett, University of Birmingham



Relative DNAPL Mobility
Density / Viscosity

Chlorinated Organic Solvent	Density (g/cm³)	Viscosity (cP)	Mobility (s/cm²)
1,2 Dichloroethane	1.25	0.84	1.47
1,1,1-Trichloroethane	1.35	0.84	1.59
Carbon tetrachloride	1.59	0.97	1.64
Chloroform	1.49	0.56	2.66
Tetrachloroethene (PCE)	1.63	0.90	1.81
Trichloroethene (TCE)	1.46	0.57	2.56

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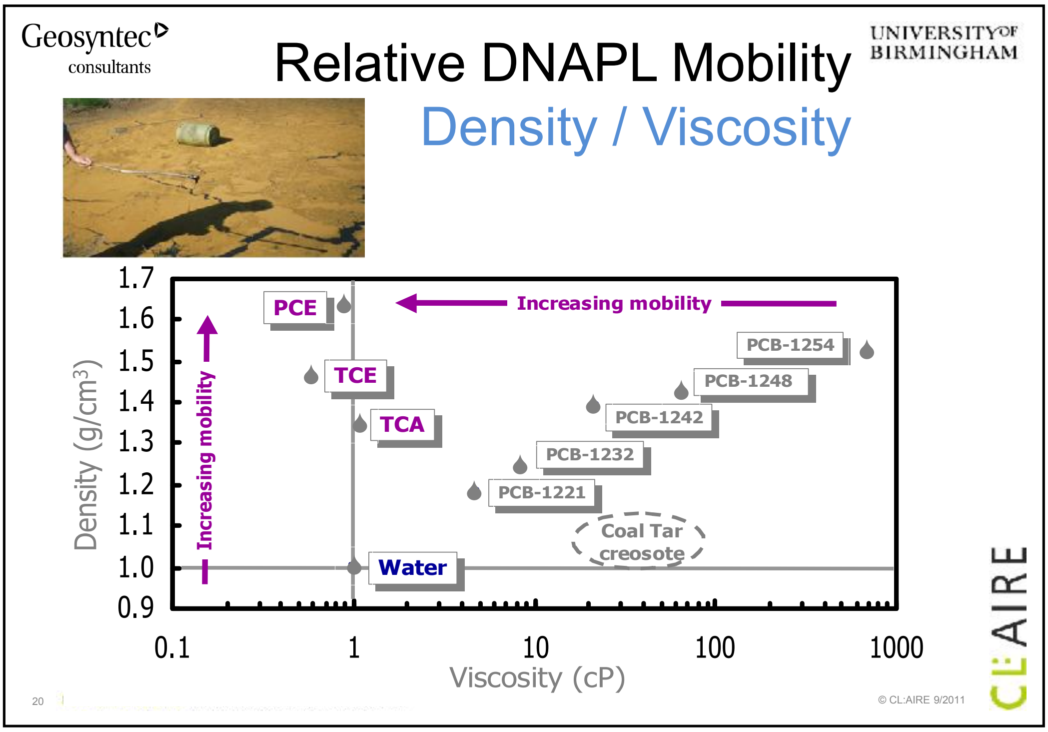

Relative DNAPL Mobility
Density / Viscosity

20

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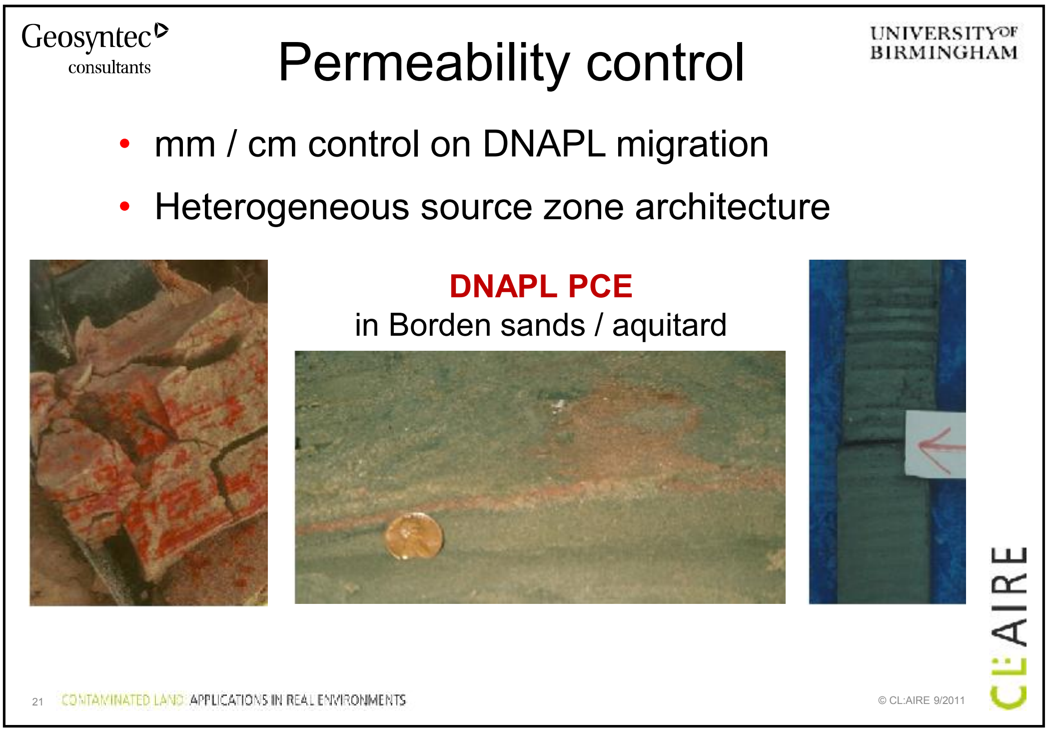

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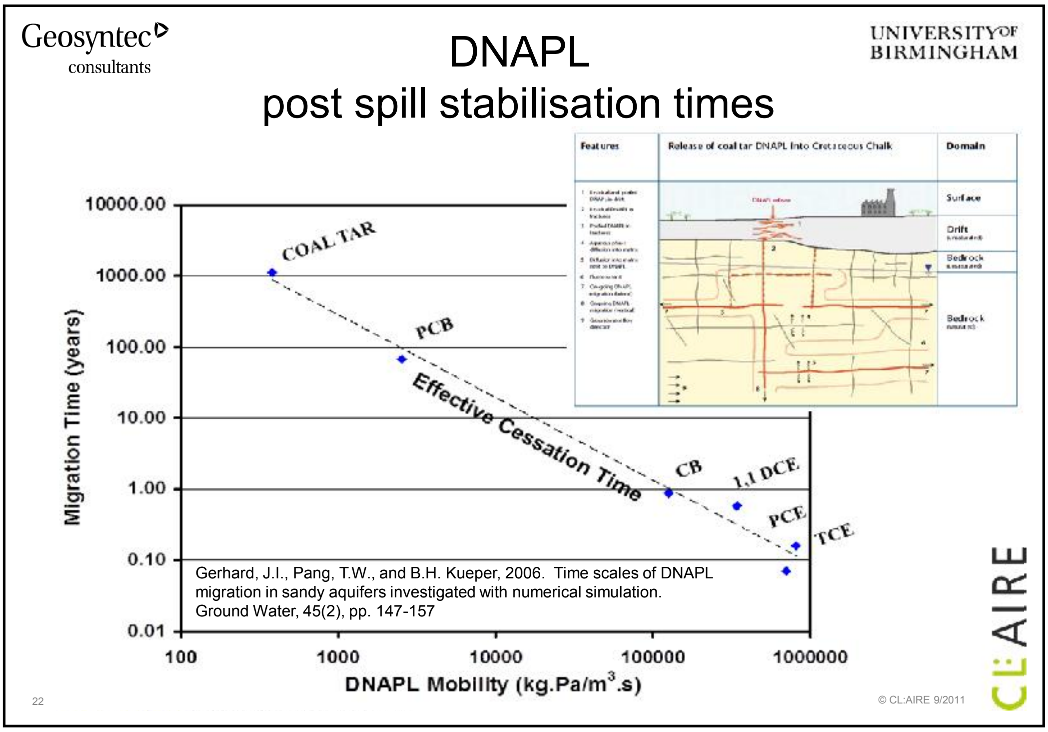
Permeability control

- mm / cm control on DNAPL migration
- Heterogeneous source zone architecture

DNAPL PCE
in Borden sands / aquitard



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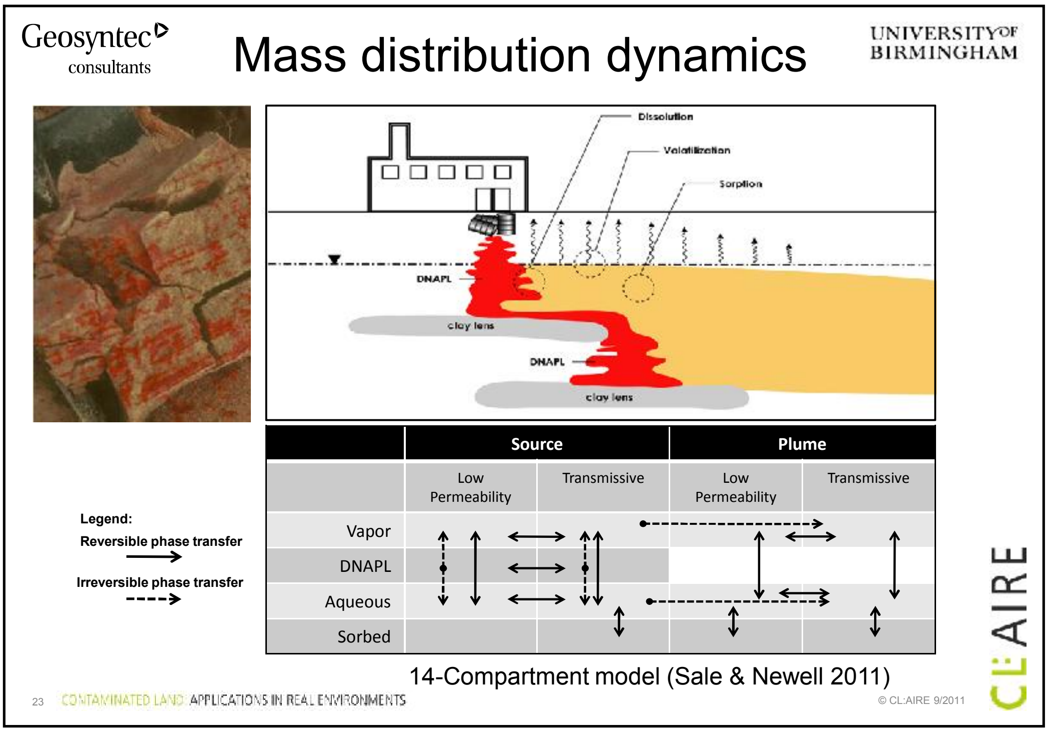
DNAPL
post spill stabilisation times

Gerhard, J.I., Pang, T.W., and B.H. Kueper, 2006. Time scales of DNAPL migration in sandy aquifers investigated with numerical simulation. Ground Water, 45(2), pp. 147-157



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Mass distribution dynamics

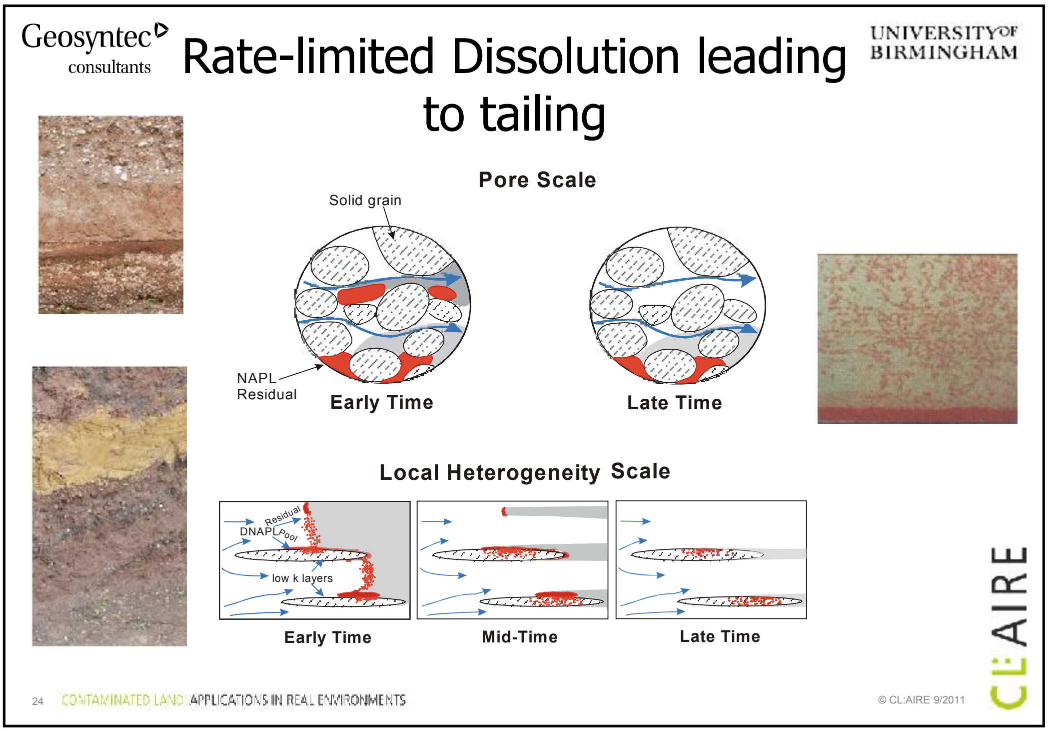
Legend:

Reversible phase transfer ⟶

Irreversible phase transfer - - - ->

	Source		Plume	
	Low Permeability	Transmissive	Low Permeability	Transmissive
Vapor				
DNAPL				
Aqueous				
Sorbed				

14-Compartment model (Sale & Newell 2011)



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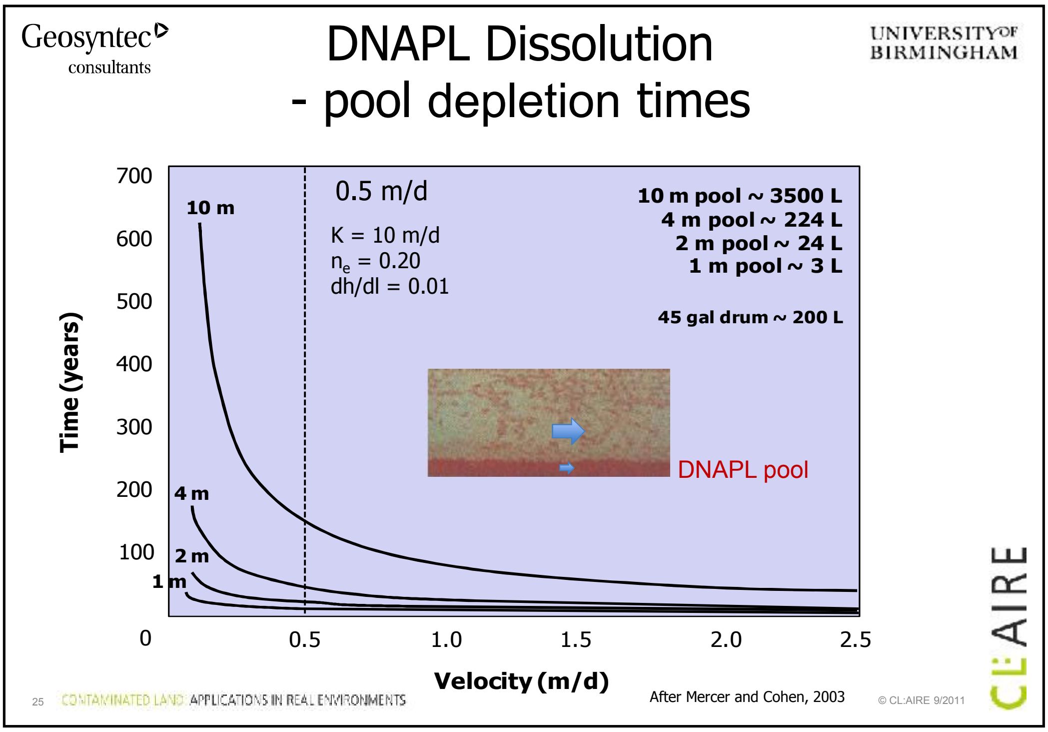
Rate-limited Dissolution leading to tailing

Pore Scale

Local Heterogeneity Scale



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DNAPL Dissolution - pool depletion times

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0.5 m/d

K = 10 m/d
n_e = 0.20
dh/dl = 0.01

10 m pool ~ 3500 L
4 m pool ~ 224 L
2 m pool ~ 24 L
1 m pool ~ 3 L

45 gal drum ~ 200 L

After Mercer and Cohen, 2003

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Solubility / Drinking water

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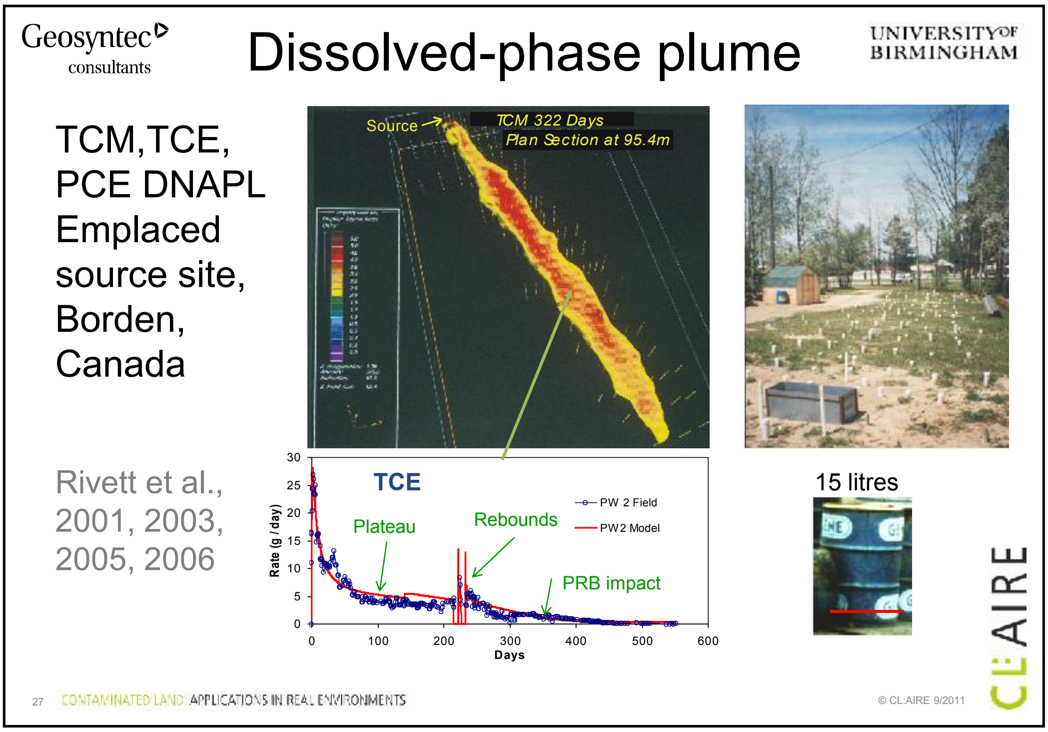
Chlorinated Organic Solvent	Solubility (mg/L)	MAC (mg/L)	Sol/MAC
1,2 Dichloroethane	8,690	0.003	3 x 10^6
1,1,1-Trichloroethane	720	0.1	7 x 10^3
CT	785	0.003	2 x 10^5
Chloroform	8,200	0.2	4 x 10^4
PCE	200	0.005	4 x 10^4
TCE	1,100	0.005	2 x 10^5

MAC is WHO maximum admissible concentration



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Dissolved-phase plume

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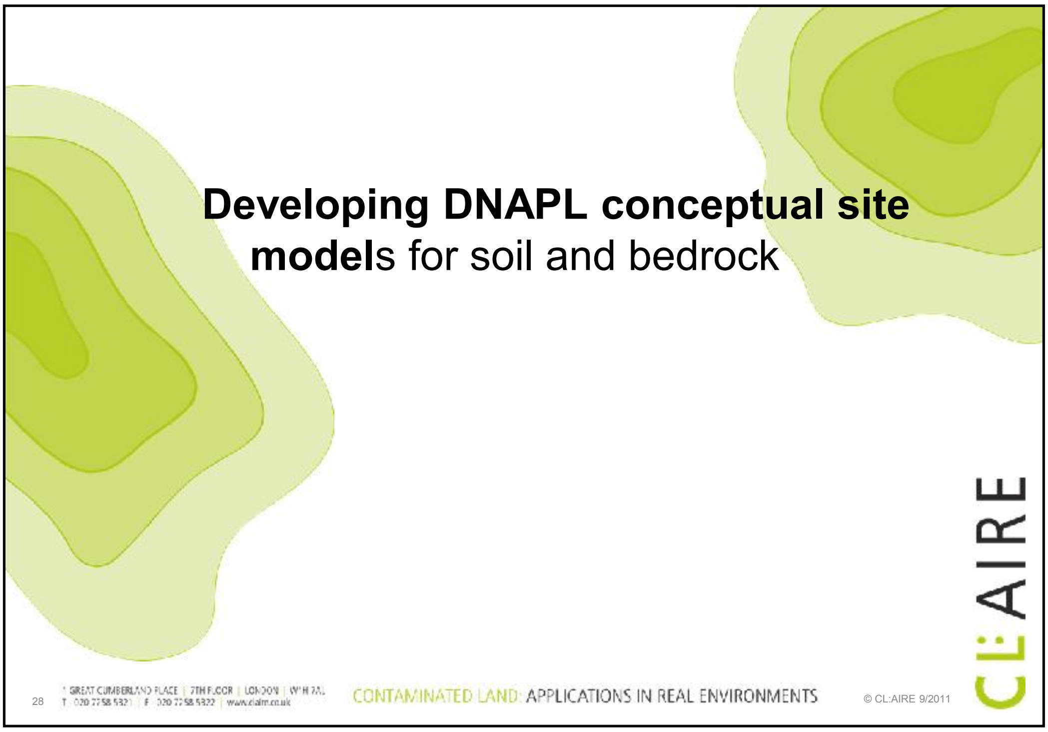
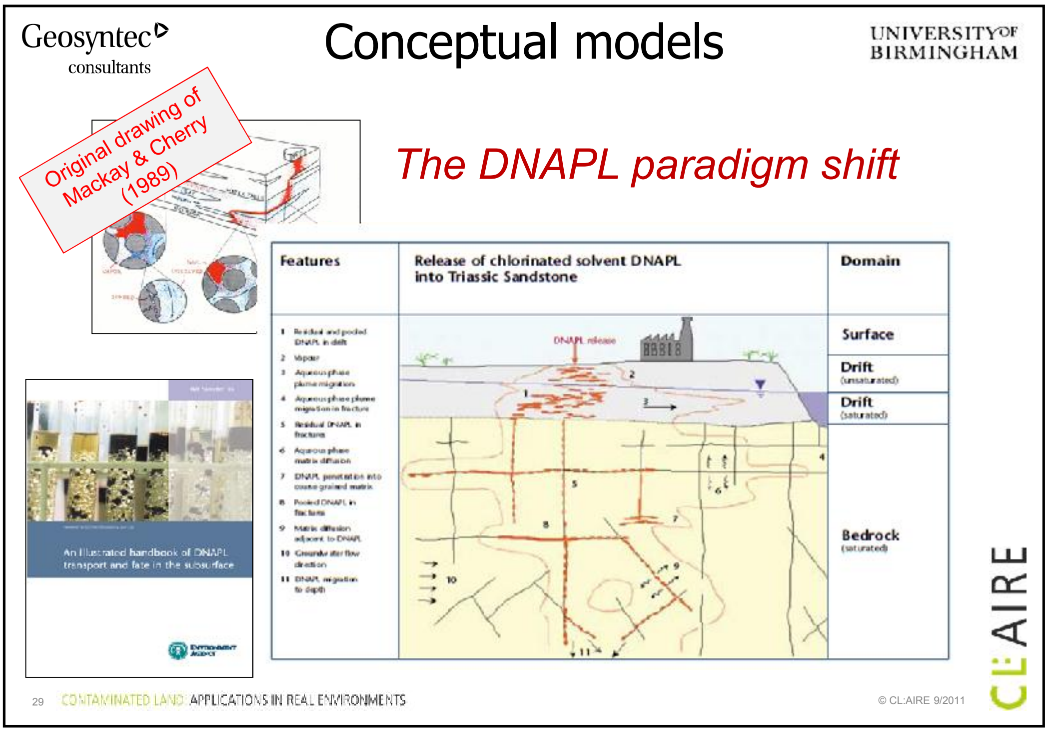
TCM,TCE, PCE DNAPL Emplaced source site, Borden, Canada

Rivett et al., 2001, 2003, 2005, 2006

15 litres



Developing DNAPL conceptual site models for soil and bedrock



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Conceptual models

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The DNAPL paradigm shift

Original drawing of Mackay & Cherry (1989)

An illustrated handbook of DNAPL transport and fate in the subsurface

Features

1 Residual and pooled DNAPL in drift
2 Vapour
3 Aqueous phase plume migration
4 Aqueous phase plume migration in fracture
5 Residual DNAPL in fractures
6 Aqueous phase matrix diffusion
7 DNAPL penetration into coarse grained matrix
8 Pooled DNAPL in fractures
9 Matrix diffusion adjacent to DNAPL
10 Groundwater flow direction
11 DNAPL migration to depth

Release of chlorinated solvent DNAPL into Triassic Sandstone

Domain

Surface
Drift (unsaturated)
Drift (saturated)
Bedrock (saturated)

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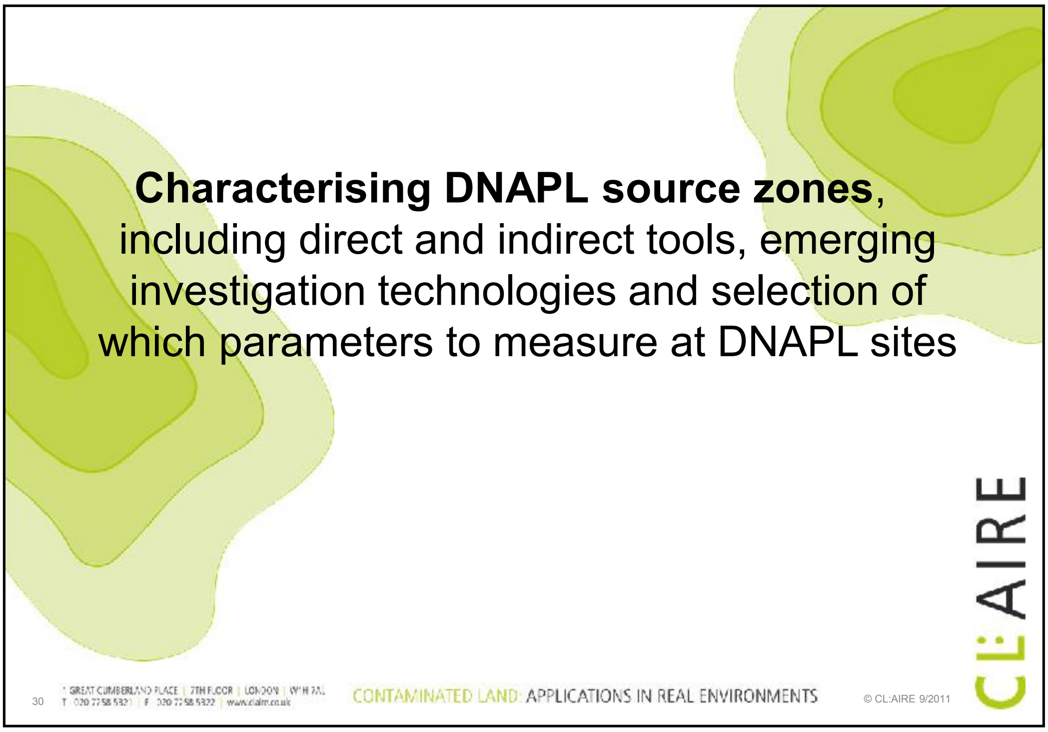

Characterising DNAPL source zones, including direct and indirect tools, emerging investigation technologies and selection of which parameters to measure at DNAPL sites

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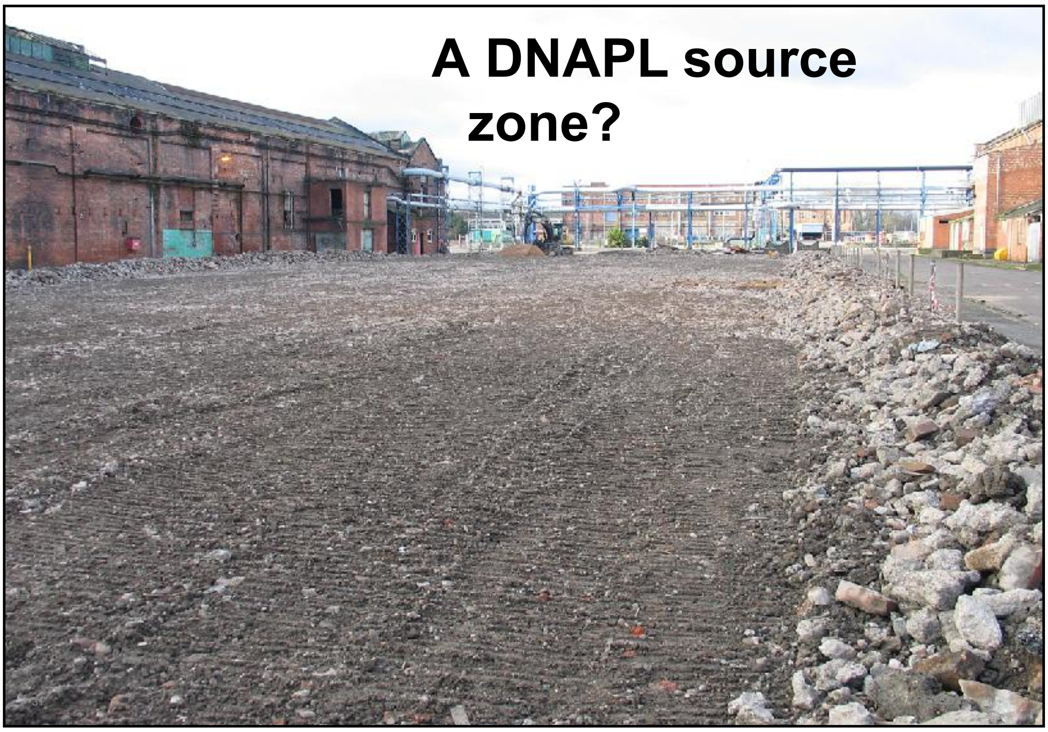
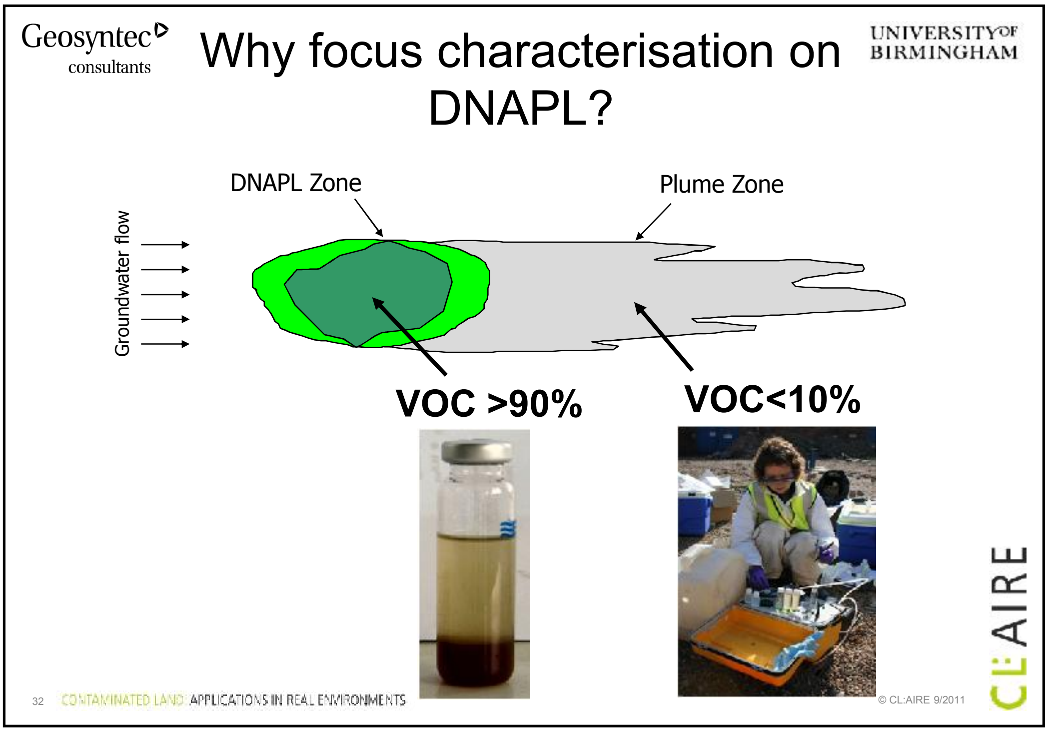


A DNAPL source zone?



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Why focus characterisation on DNAPL?

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VOC >90%

VOC<10%

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Multiple lines of evidence

Direct measurement	Indirect measurement
Visual observation	Site history
Enhanced visual methods	Soil gas survey
Drive point tools	Soil (partitioning threshold)
	Groundwater (Effective solubility)
	Partitioning tracer test

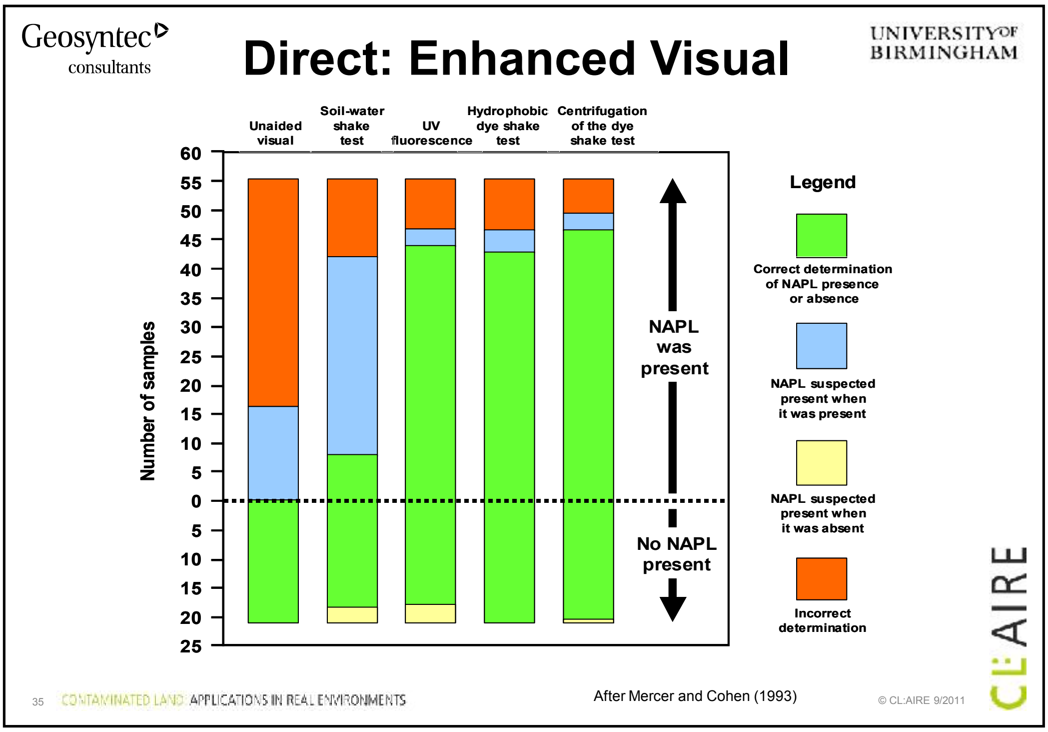
- **No SINGLE technique available to characterise a DNAPL site**
- **Generally poor resolution, and resolution decreases with depth and hydrogeological complexity**
- **Resolution typically constrains selection, application and performance assessment of remediation technologies**

Direct: Visual observation

From core or grab samples
- Rare at chlorinated solvent sites
- Common at coal tar sites

* IFT = 7 dynes/cm
* Density ≈ 1.4 g/cm^3
* Contact angle 30˚

Samples recovered during from pumping from wells
- Typically requires pooled DNAPL



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Direct: Enhanced Visual

After Mercer and Cohen (1993)

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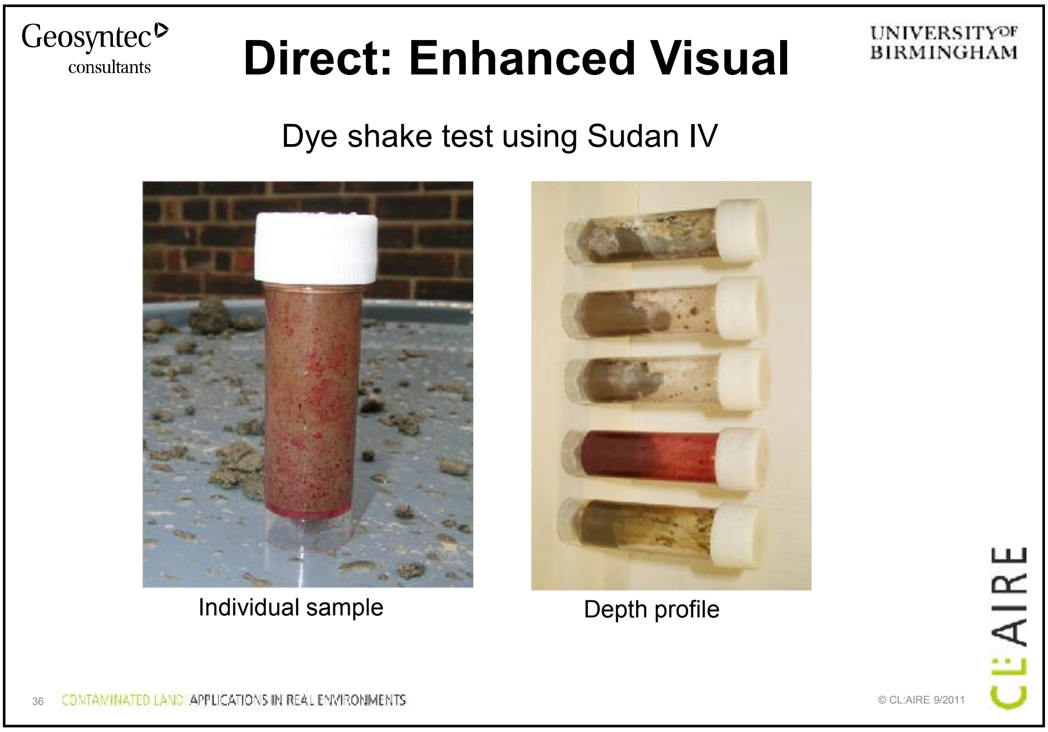

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Direct: Enhanced Visual

Dye shake test using Sudan IV

Individual sample

Depth profile

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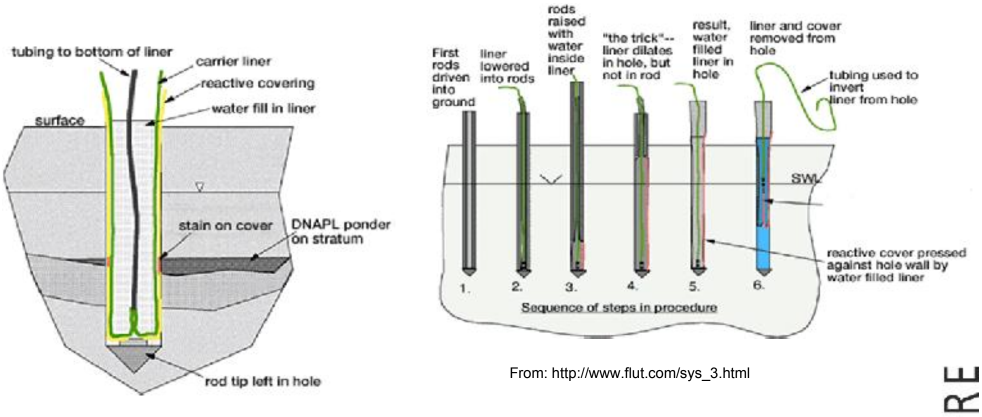
Direct: Enhanced visual

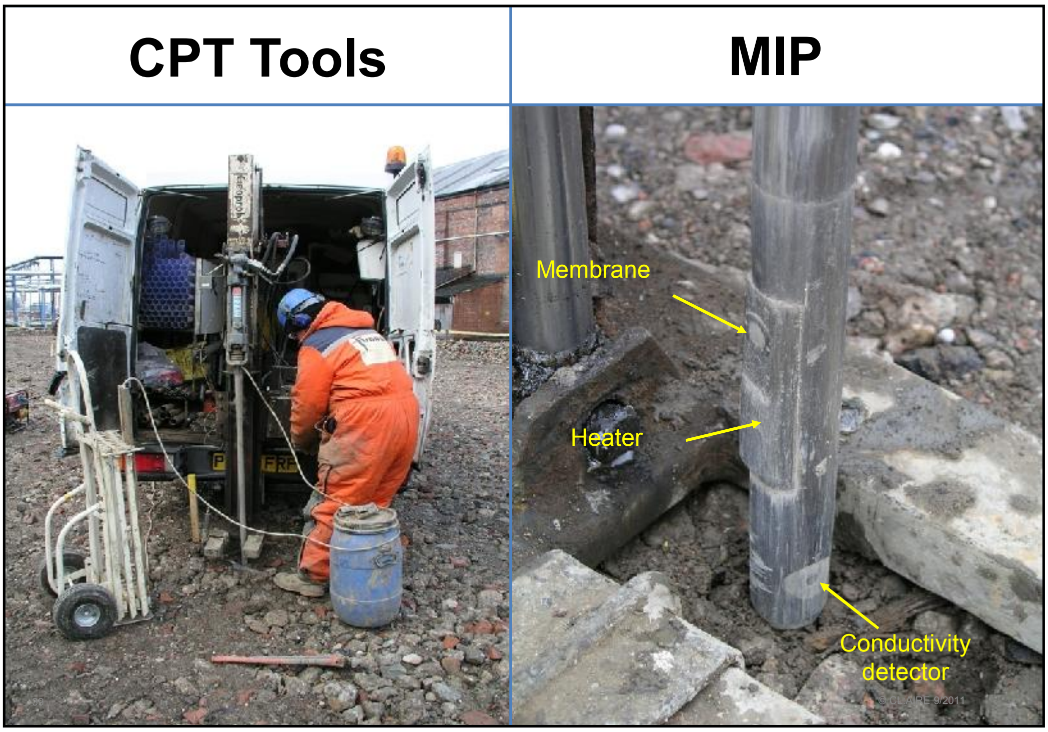
Flexible liner underground everting membrane [Flute]



From: http://www.flut.com/sys_3.html

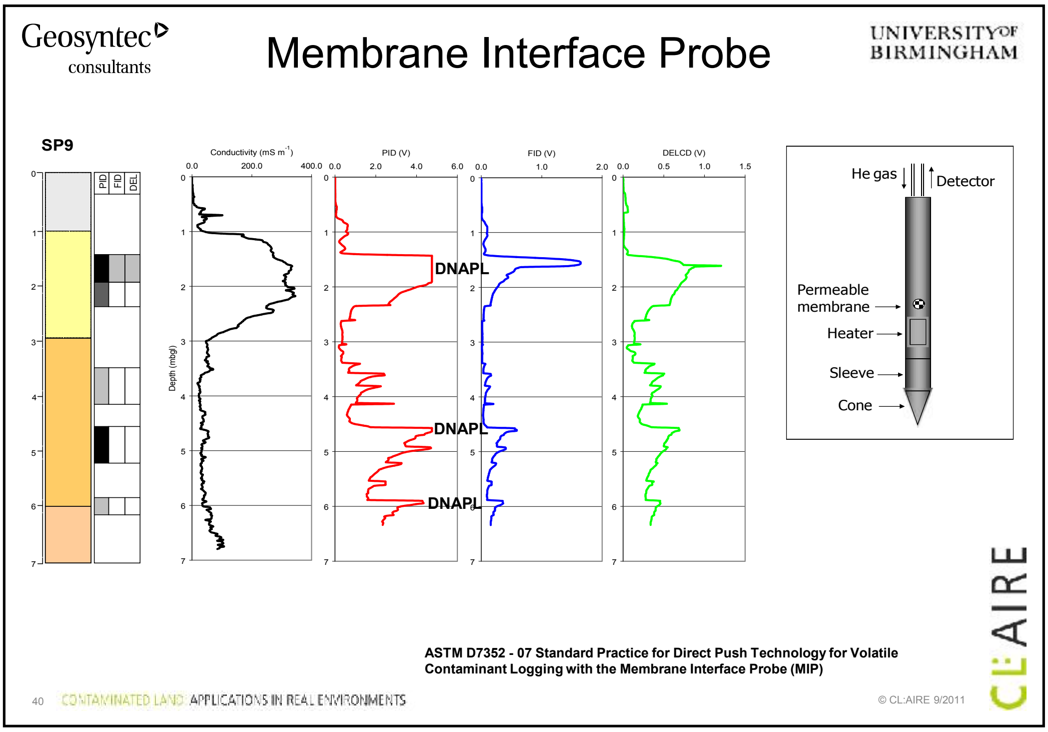
Direct: Drive Point Tools

Method	Advantages	Disadvantages
Video imaging **[GeoVis]**	**Can be coupled with lithological logs** **Data easy to interpret in suitable soil matrix**	**Limited by lithology** **Transparent DNAPL not visible** **Clays may smear the camera window**
Membrane Interface Probe **[MIP]**	**Can be coupled with lithological logs** **Range of detectors [FID, PID, ECD]** **Excellent screening level data**	**Limited by lithology** **Semi-quantitative** **High operator skill required**
Laser Induced fluorescence **[LIF]**	**Can be coupled with lithological logs** **Simple detection methodology** **Excellent screening level data**	**Limited by lithology** **Semi-quantitative** **False positives may be detected**
Dye-LIF	**Can be coupled with lithological logs** **Applicable to non-fluorescing compounds** **Excellent screening level data**	**Limited by lithology** **Still under development**
TarGOST	**Can be coupled with lithological logs** **Applicable to coal tar compound** **Excellent screening level data**	**Limited by lithology** **Only applicable to coal tar compounds**



CPT Tools

MIP



Membrane Interface Probe

ASTM D7352 - 07 Standard Practice for Direct Push Technology for Volatile Contaminant Logging with the Membrane Interface Probe (MIP)

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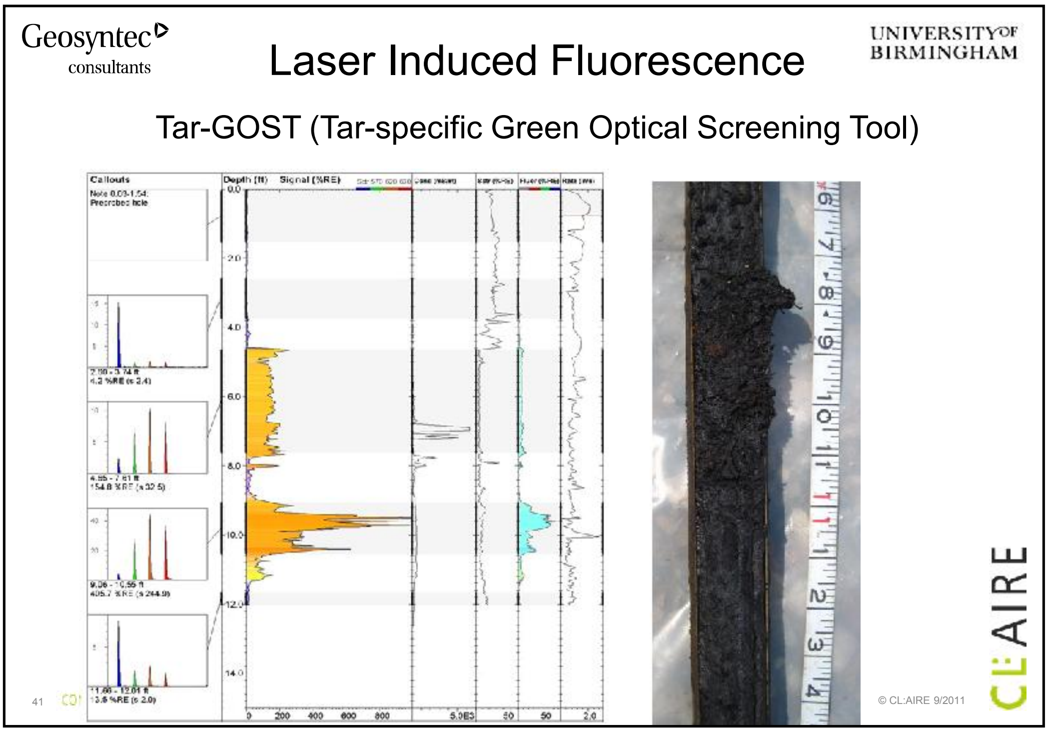

Laser Induced Fluorescence

Tar-GOST (Tar-specific Green Optical Screening Tool)

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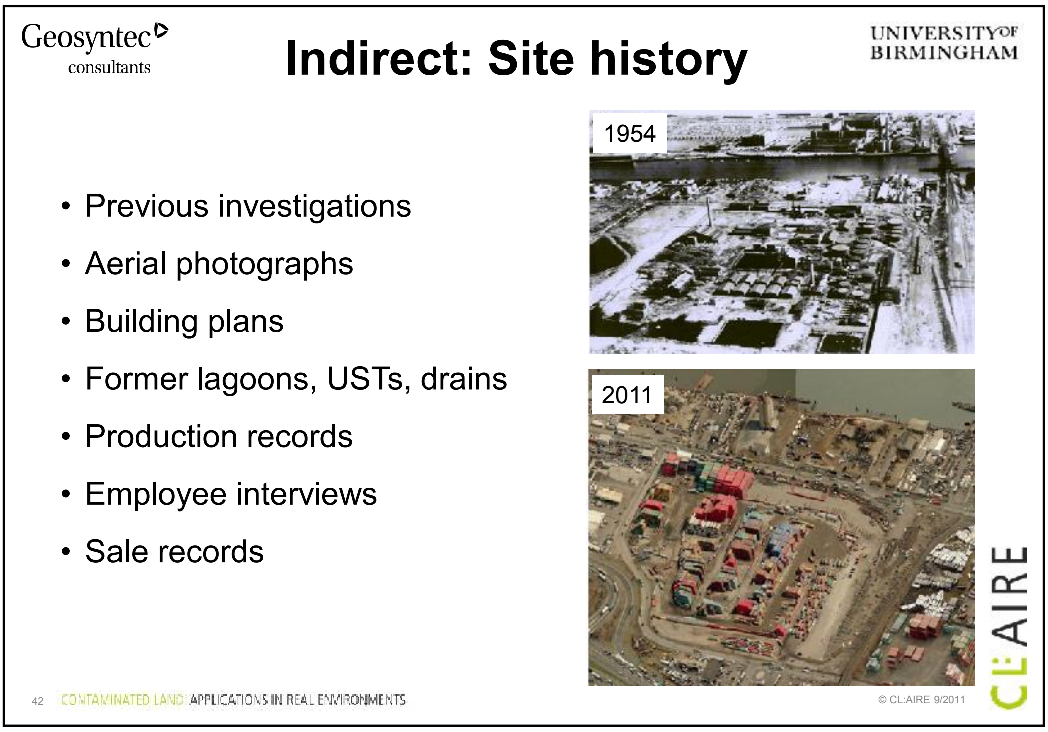

Indirect: Site history

- Previous investigations
- Aerial photographs
- Building plans
- Former lagoons, USTs, drains
- Production records
- Employee interviews
- Sale records

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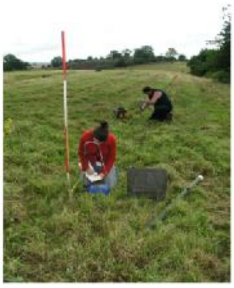
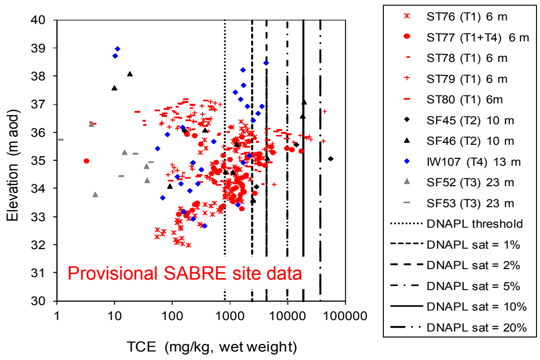
Indirect: Soil gas survey

- Vapour phase plume may be coincident with DNAPL source zone
- Avoid mistaking vapours from a groundwater plume from vapours derived from DNAPL
- Requires other supporting lines of evidence
- Methods include shallow soil spike survey or sampling monitoring wells (active or passive)
- Radon-222 has been used to infer DNAPL presence



Indirect:
Soil partitioning threshold

$$C_D = \frac{S_r \phi \rho_N 10^6}{\rho b} + C^T$$



Where:

C_D is soil concentration (mg/kg) corresponding to threshold DNAPL saturation

S_r is threshold DNAPL saturation

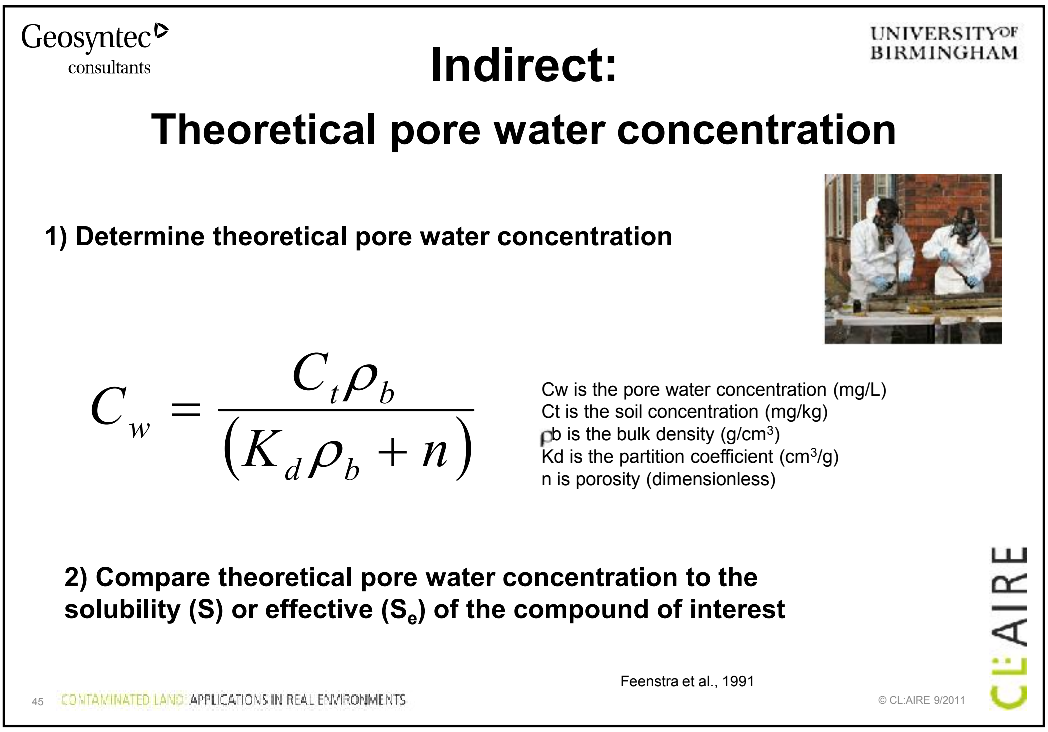
ϕ s the porosity

ρ_N is DNAPL density (g/cc)

ρ_b is dry soil bulk density (g/cc)

C^T is amount of contaminant (mg/kg) in the samples, including aqueous, vapour and sorbed

Kueper and Davies, 2009



Indirect:
Theoretical pore water concentration

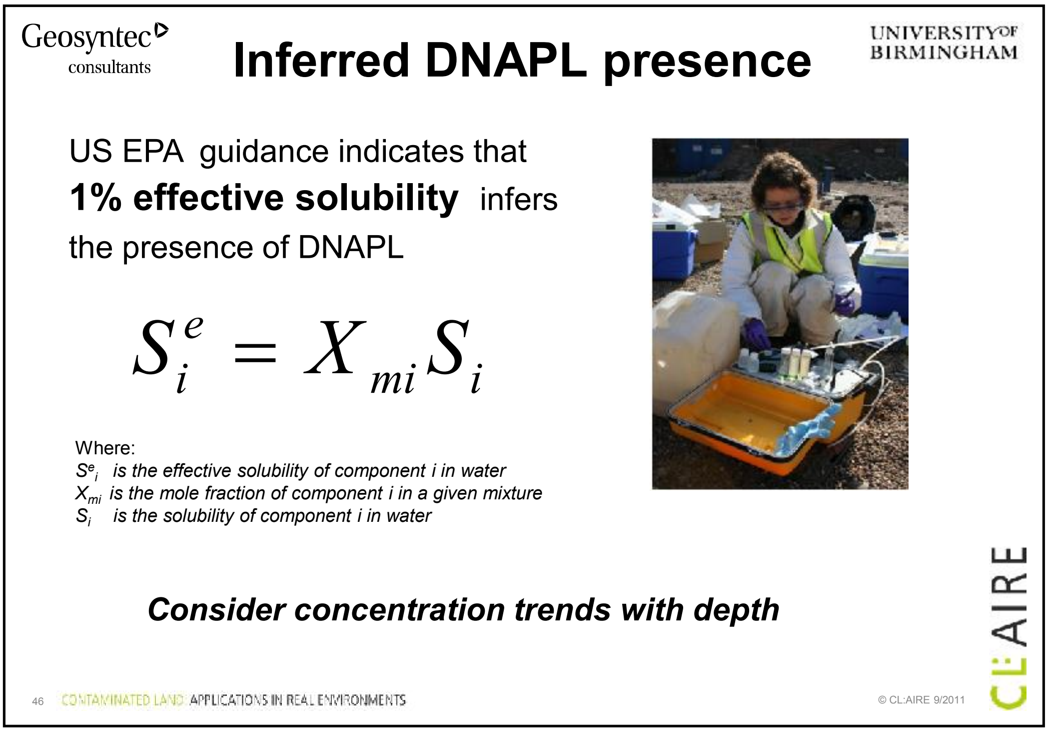
1) Determine theoretical pore water concentration

$$C_w = \frac{C_t \rho_b}{\left(K_d \rho_b + n\right)}$$

Cw is the pore water concentration (mg/L)
Ct is the soil concentration (mg/kg)
ρb is the bulk density (g/cm^3)
Kd is the partition coefficient (cm^3/g)
n is porosity (dimensionless)

2) Compare theoretical pore water concentration to the solubility (S) or effective (S_e) of the compound of interest

Feenstra et al., 1991



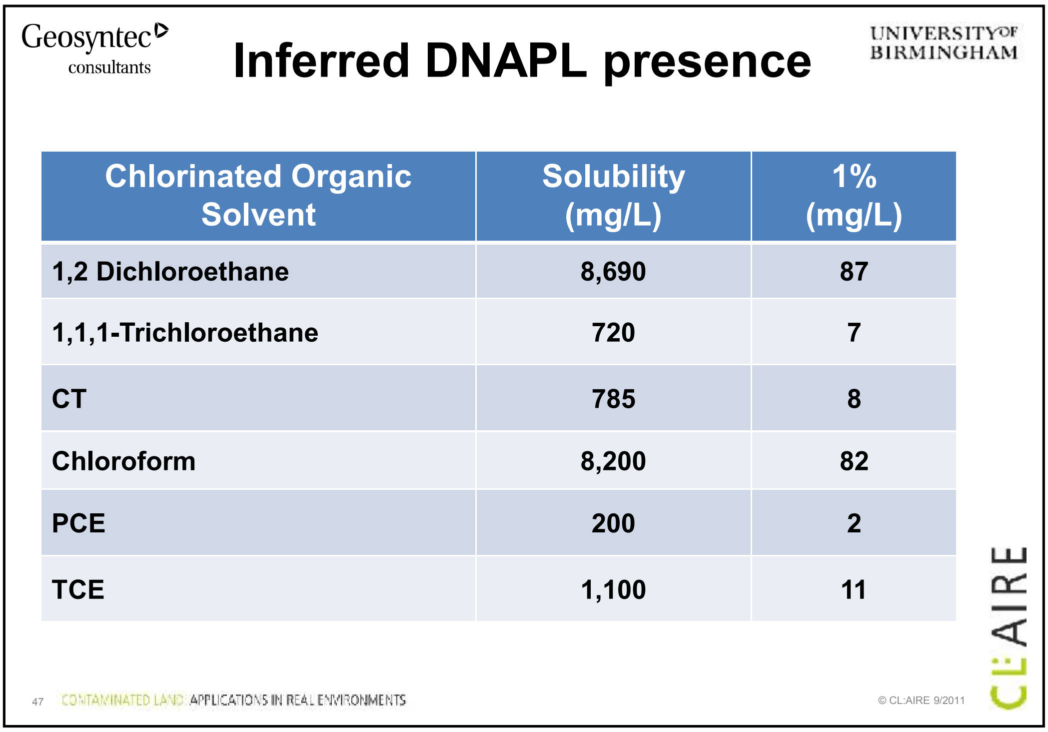
Inferred DNAPL presence

US EPA guidance indicates that **1% effective solubility** infers the presence of DNAPL

$$S_i^e = X_{mi} S_i$$

Where:
S^e_i is the effective solubility of component i in water
X_{mi} is the mole fraction of component i in a given mixture
S_i is the solubility of component i in water

Consider concentration trends with depth



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Inferred DNAPL presence

Chlorinated Organic Solvent	Solubility (mg/L)	1% (mg/L)
1,2 Dichloroethane	**8,690**	**87**
1,1,1-Trichloroethane	**720**	**7**
CT	**785**	**8**
Chloroform	**8,200**	**82**
PCE	**200**	**2**
TCE	**1,100**	**11**

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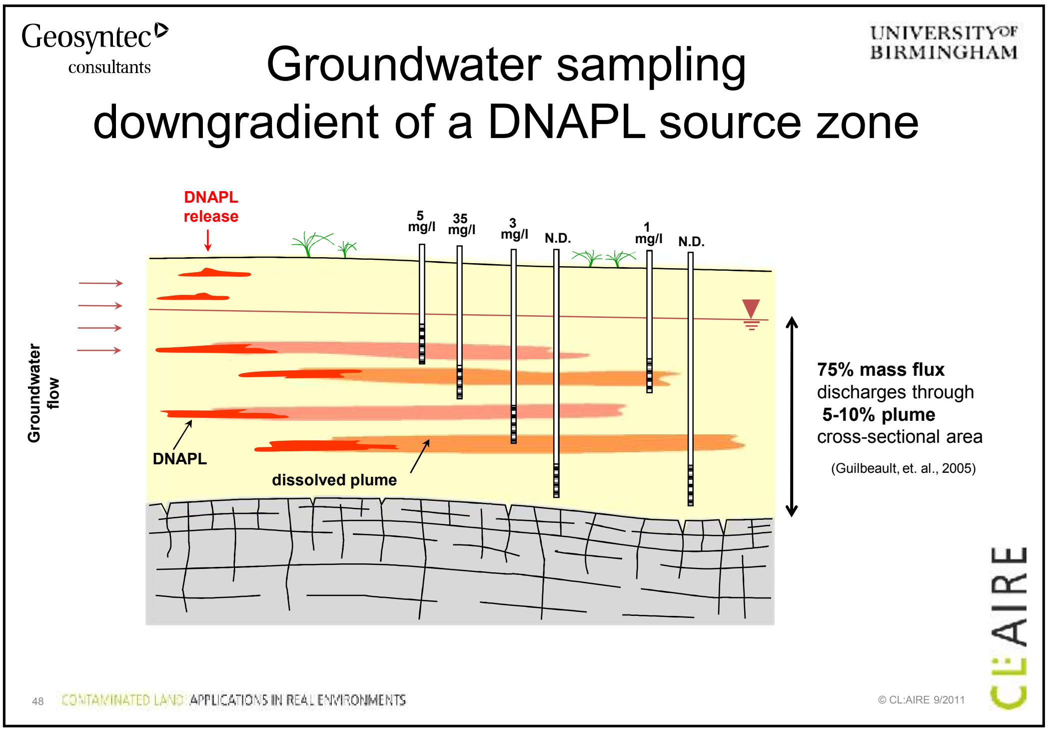

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Groundwater sampling downgradient of a DNAPL source zone

75% mass flux discharges through **5-10% plume** cross-sectional area

(Guilbeault, et. al., 2005)

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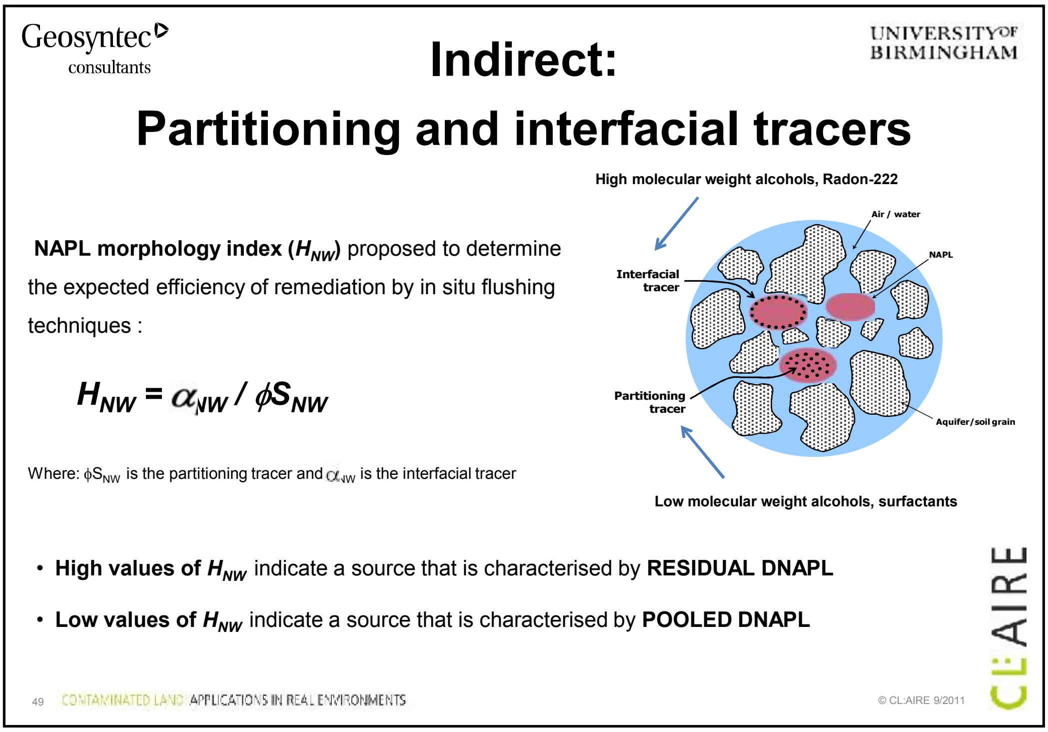


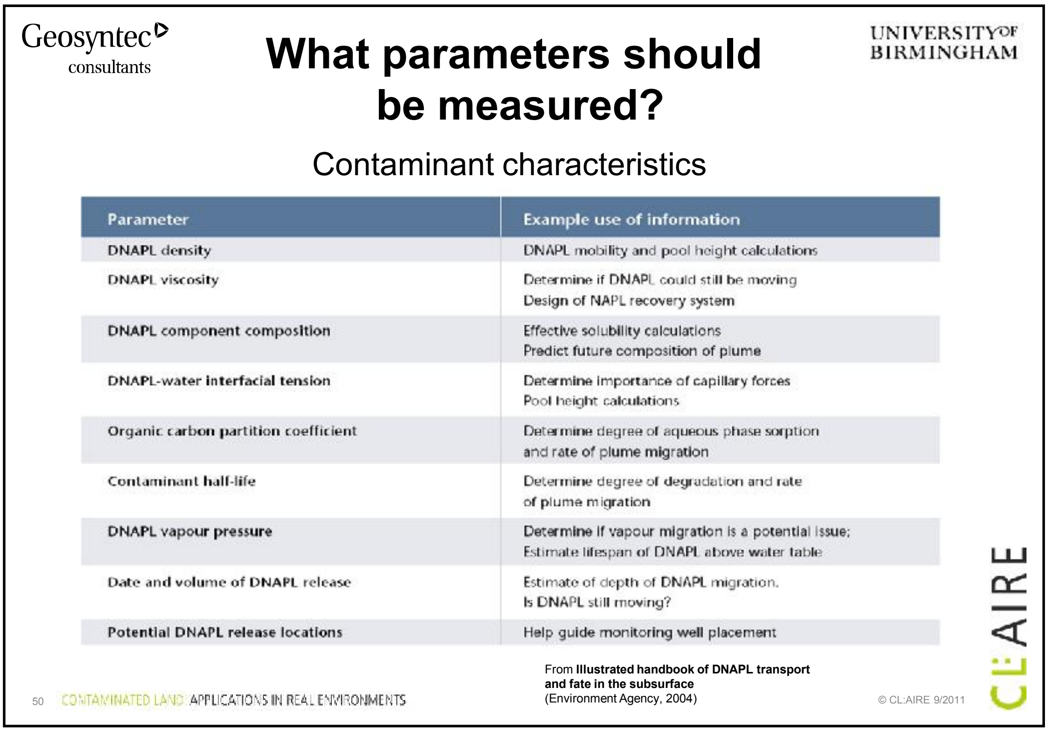
Indirect:
Partitioning and interfacial tracers

NAPL morphology index (H_{NW}) proposed to determine the expected efficiency of remediation by in situ flushing techniques :

$$H_{NW} = \alpha_{NW} / \phi S_{NW}$$

Where: ϕS_{NW} is the partitioning tracer and α_{NW} is the interfacial tracer

- **High values of H_{NW}** indicate a source that is characterised by **RESIDUAL DNAPL**
- **Low values of H_{NW}** indicate a source that is characterised by **POOLED DNAPL**

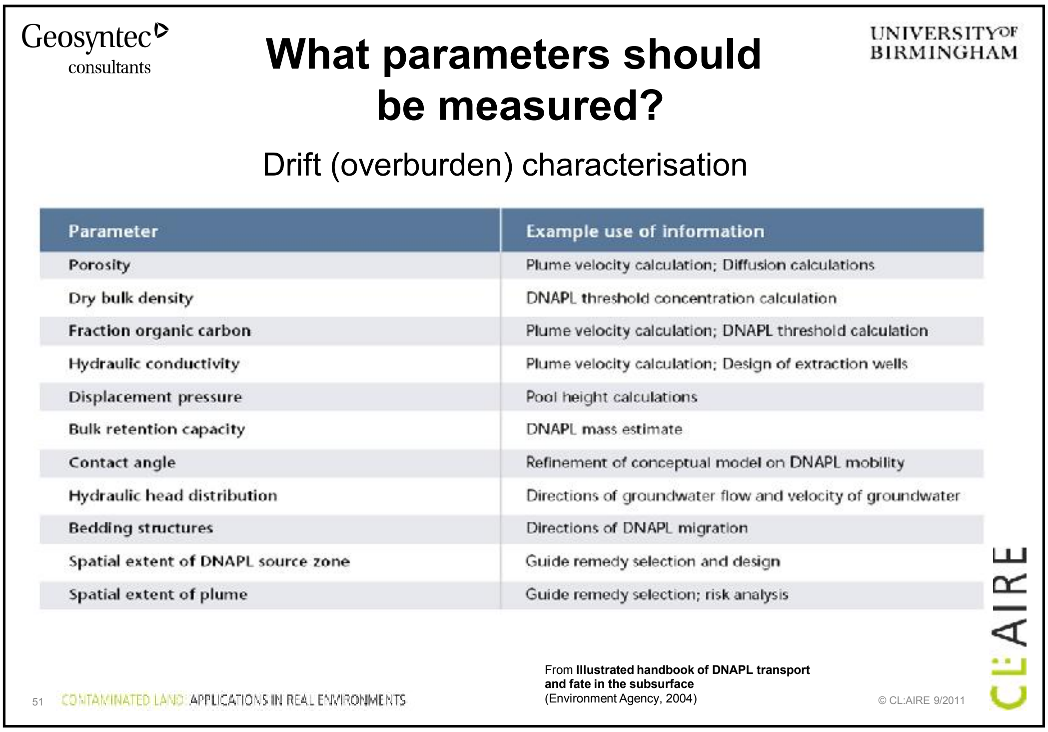


What parameters should be measured?

Contaminant characteristics

Parameter	Example use of information
DNAPL density	DNAPL mobility and pool height calculations
DNAPL viscosity	Determine if DNAPL could still be moving Design of NAPL recovery system
DNAPL component composition	Effective solubility calculations Predict future composition of plume
DNAPL-water interfacial tension	Determine importance of capillary forces Pool height calculations
Organic carbon partition coefficient	Determine degree of aqueous phase sorption and rate of plume migration
Contaminant half-life	Determine degree of degradation and rate of plume migration
DNAPL vapour pressure	Determine if vapour migration is a potential issue; Estimate lifespan of DNAPL above water table
Date and volume of DNAPL release	Estimate of depth of DNAPL migration. Is DNAPL still moving?
Potential DNAPL release locations	Help guide monitoring well placement

From **Illustrated handbook of DNAPL transport and fate in the subsurface**
(Environment Agency, 2004)



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What parameters should be measured?

Drift (overburden) characterisation

Parameter	Example use of information
Porosity	Plume velocity calculation; Diffusion calculations
Dry bulk density	DNAPL threshold concentration calculation
Fraction organic carbon	Plume velocity calculation; DNAPL threshold calculation
Hydraulic conductivity	Plume velocity calculation; Design of extraction wells
Displacement pressure	Pool height calculations
Bulk retention capacity	DNAPL mass estimate
Contact angle	Refinement of conceptual model on DNAPL mobility
Hydraulic head distribution	Directions of groundwater flow and velocity of groundwater
Bedding structures	Directions of DNAPL migration
Spatial extent of DNAPL source zone	Guide remedy selection and design
Spatial extent of plume	Guide remedy selection; risk analysis

From **Illustrated handbook of DNAPL transport and fate in the subsurface** (Environment Agency, 2004)

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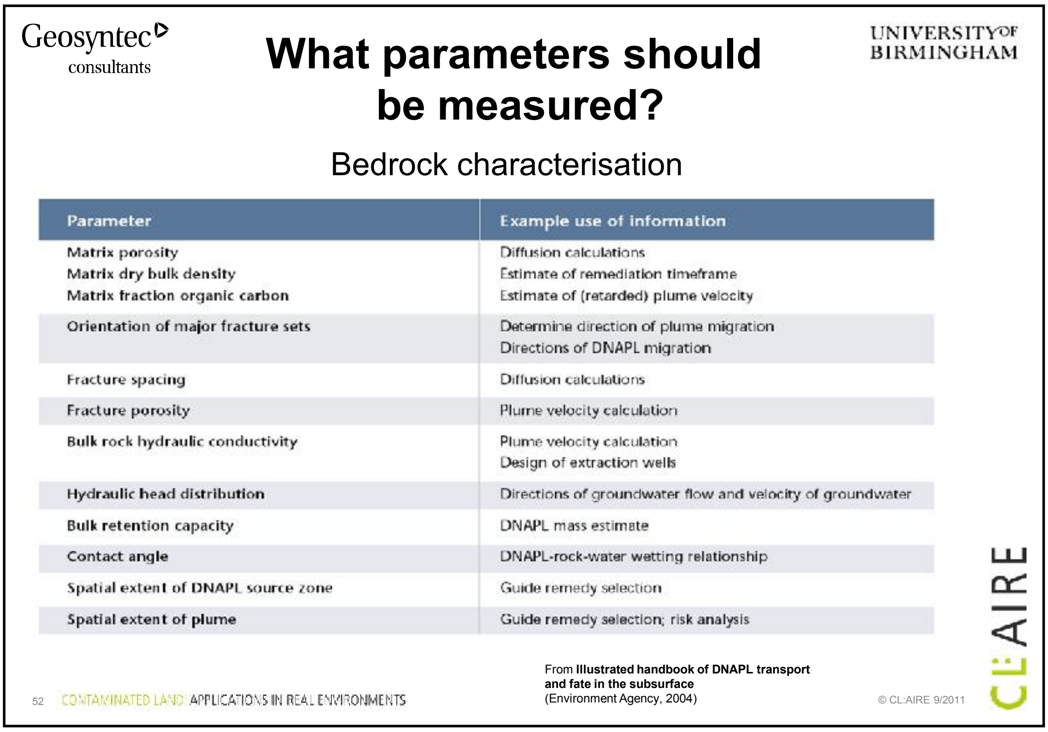

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What parameters should be measured?

Bedrock characterisation

Parameter	Example use of information
Matrix porosity	Diffusion calculations
Matrix dry bulk density	Estimate of remediation timeframe
Matrix fraction organic carbon	Estimate of (retarded) plume velocity
Orientation of major fracture sets	Determine direction of plume migration Directions of DNAPL migration
Fracture spacing	Diffusion calculations
Fracture porosity	Plume velocity calculation
Bulk rock hydraulic conductivity	Plume velocity calculation Design of extraction wells
Hydraulic head distribution	Directions of groundwater flow and velocity of groundwater
Bulk retention capacity	DNAPL mass estimate
Contact angle	DNAPL-rock-water wetting relationship
Spatial extent of DNAPL source zone	Guide remedy selection
Spatial extent of plume	Guide remedy selection; risk analysis

From **Illustrated handbook of DNAPL transport and fate in the subsurface** (Environment Agency, 2004)

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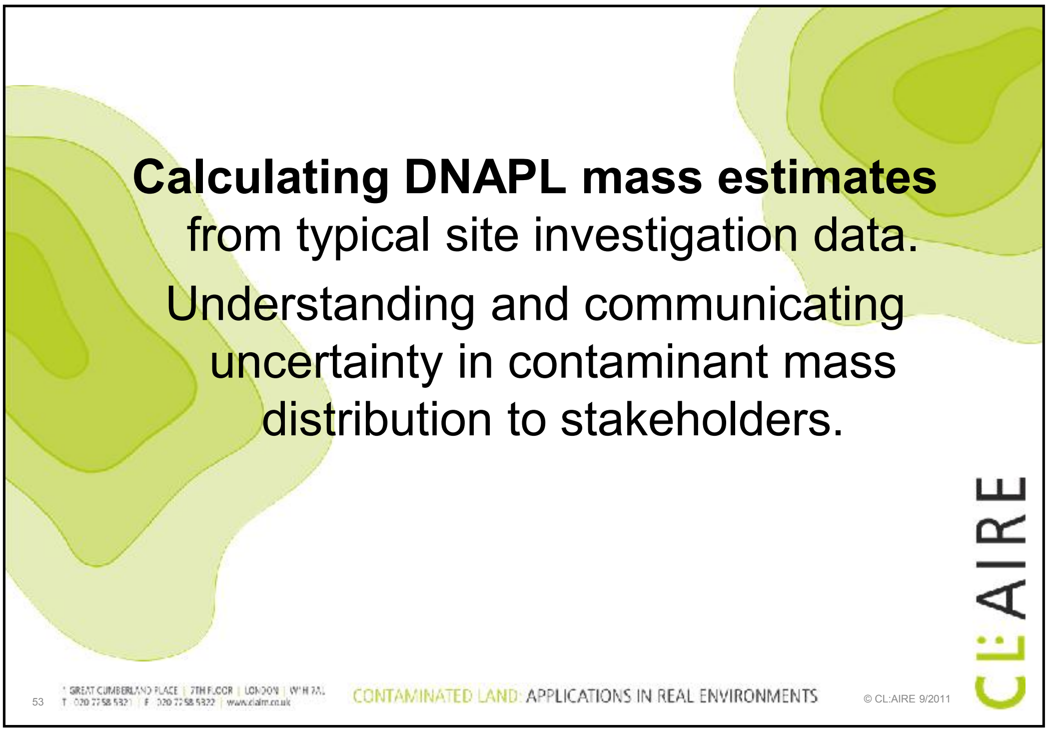
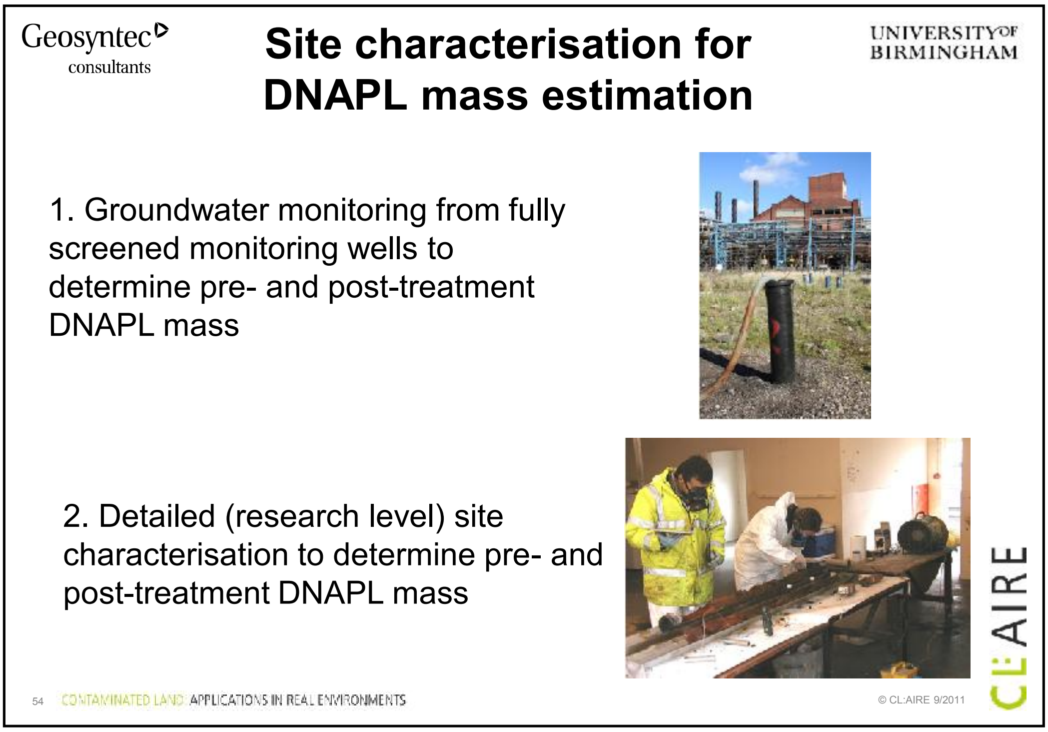


Calculating DNAPL mass estimates from typical site investigation data.

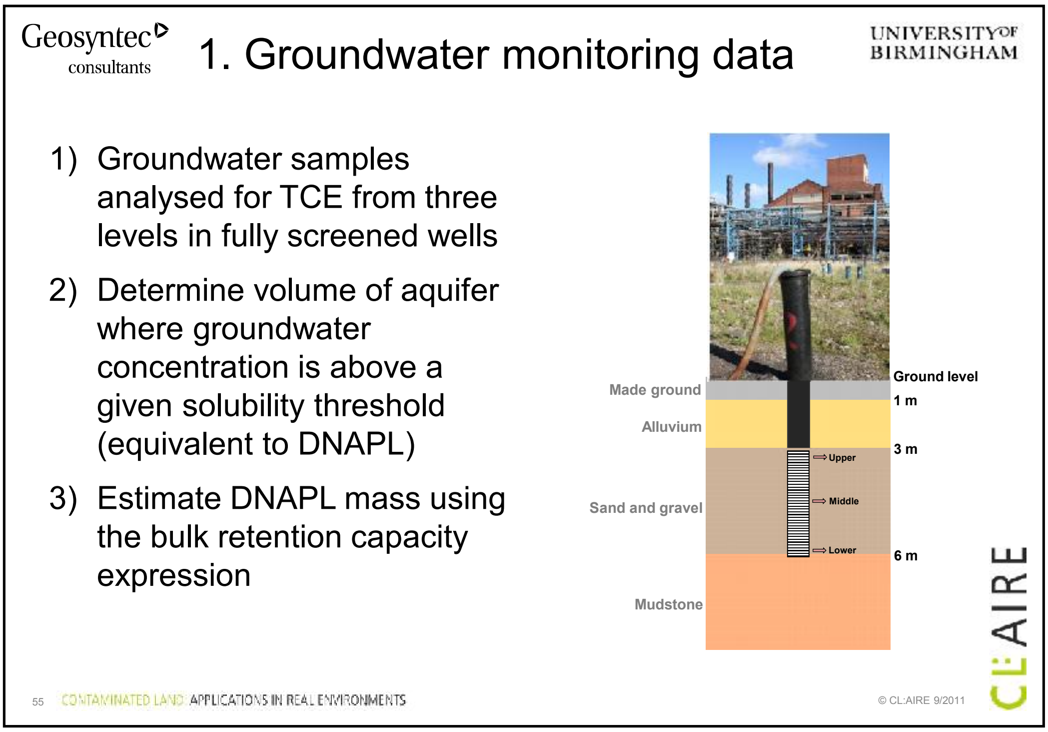
Understanding and communicating uncertainty in contaminant mass distribution to stakeholders.



Site characterisation for DNAPL mass estimation

1. Groundwater monitoring from fully screened monitoring wells to determine pre- and post-treatment DNAPL mass

2. Detailed (research level) site characterisation to determine pre- and post-treatment DNAPL mass



1. Groundwater monitoring data

1) Groundwater samples analysed for TCE from three levels in fully screened wells
2) Determine volume of aquifer where groundwater concentration is above a given solubility threshold (equivalent to DNAPL)
3) Estimate DNAPL mass using the bulk retention capacity expression

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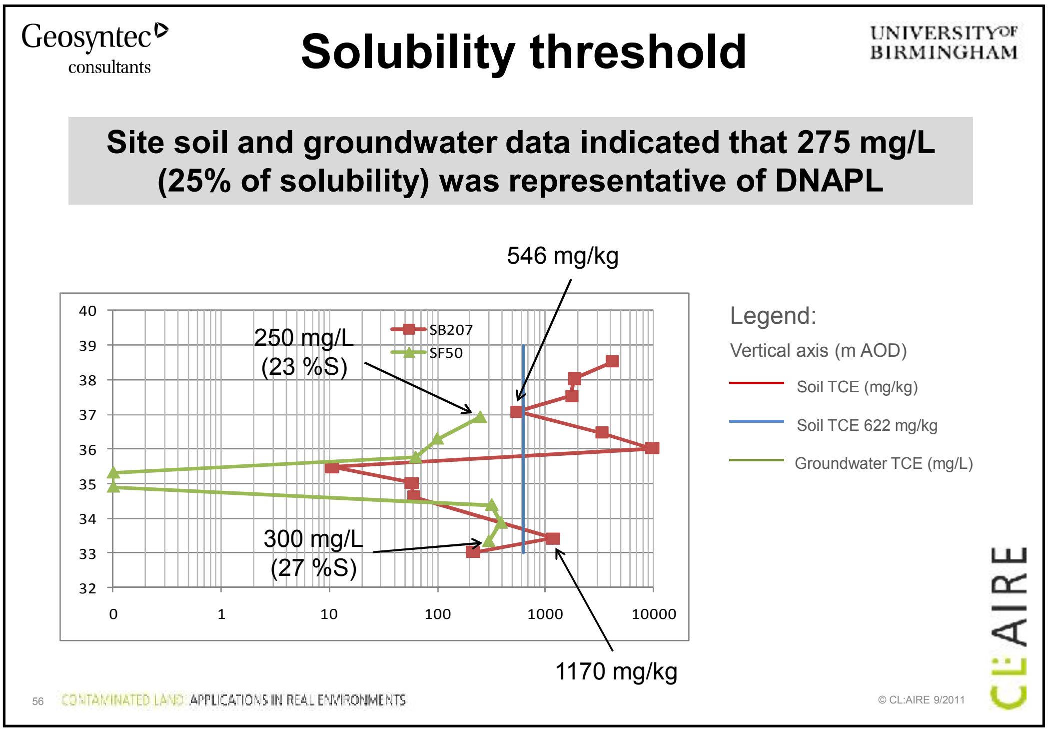

Solubility threshold

Site soil and groundwater data indicated that 275 mg/L (25% of solubility) was representative of DNAPL

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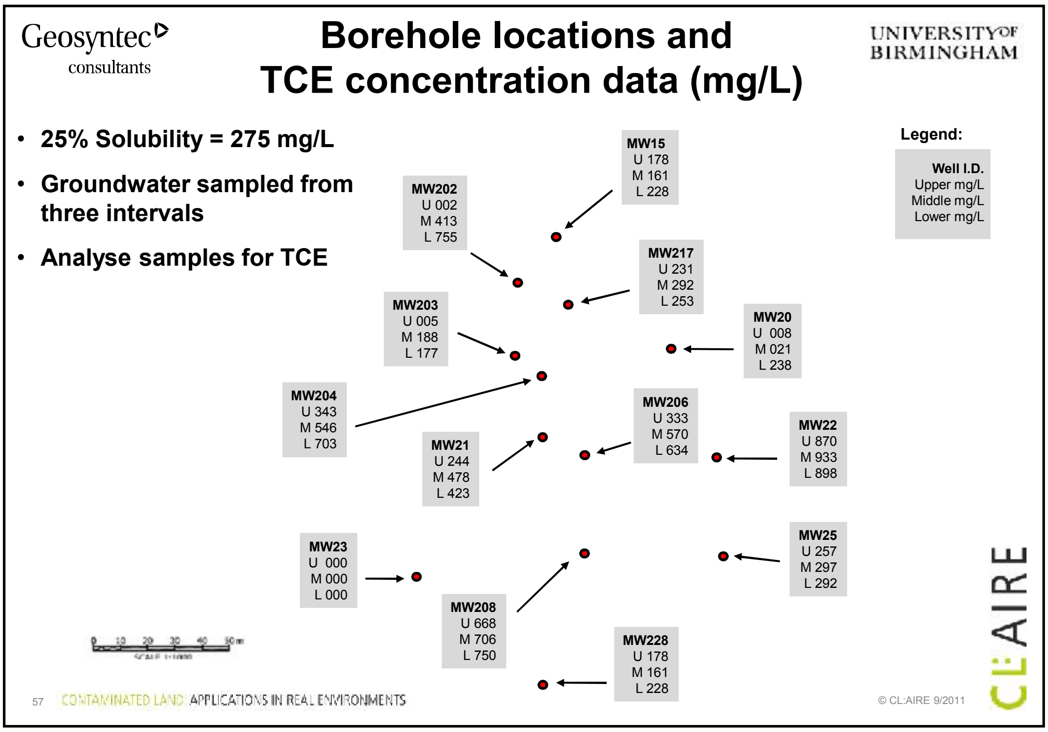

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Borehole locations and TCE concentration data (mg/L)

- **25% Solubility = 275 mg/L**
- **Groundwater sampled from three intervals**
- **Analyse samples for TCE**

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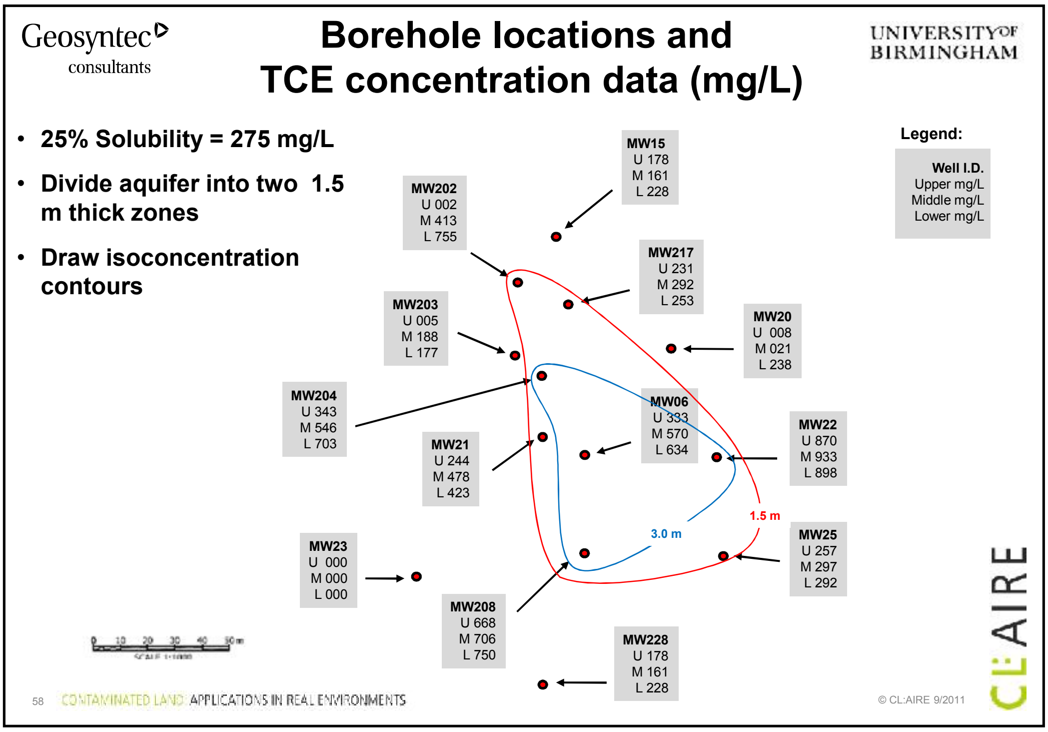

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Borehole locations and TCE concentration data (mg/L)

- **25% Solubility = 275 mg/L**
- **Divide aquifer into two 1.5 m thick zones**
- **Draw isoconcentration contours**

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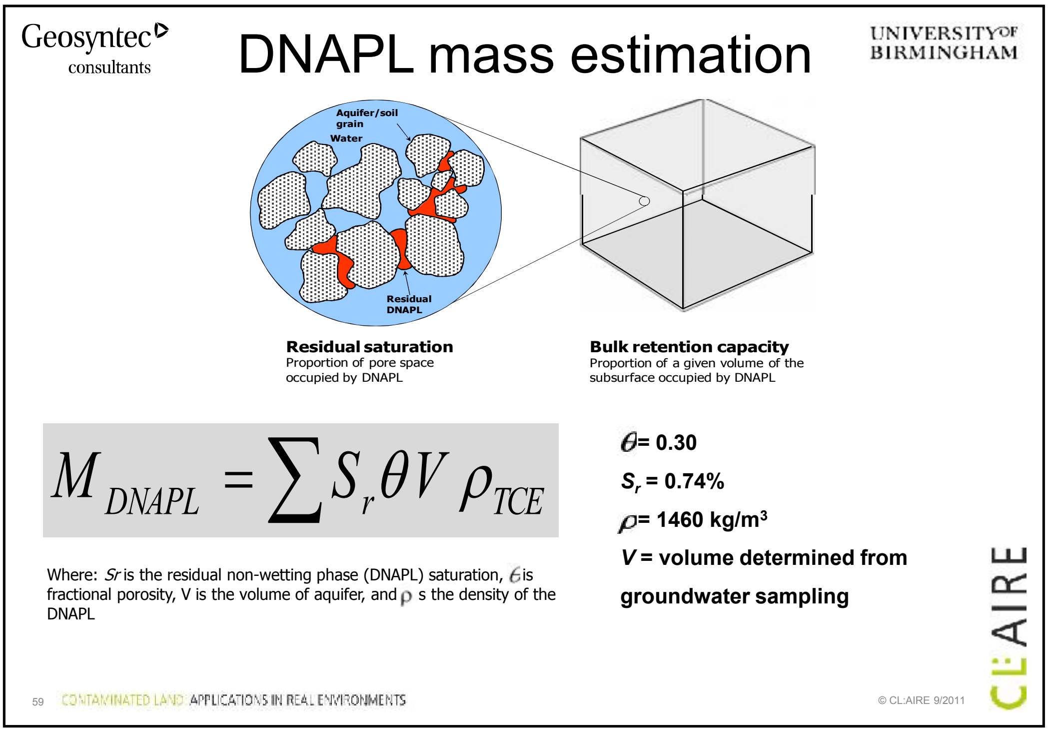

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DNAPL mass estimation

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Residual saturation
Proportion of pore space occupied by DNAPL

Bulk retention capacity
Proportion of a given volume of the subsurface occupied by DNAPL

$$M_{DNAPL} = \sum S_r \theta V \rho_{TCE}$$

Where: Sr is the residual non-wetting phase (DNAPL) saturation, θ is fractional porosity, V is the volume of aquifer, and ρ s the density of the DNAPL

θ= 0.30
S_r = 0.74%
ρ= 1460 kg/m^3
***V* = volume determined from groundwater sampling**

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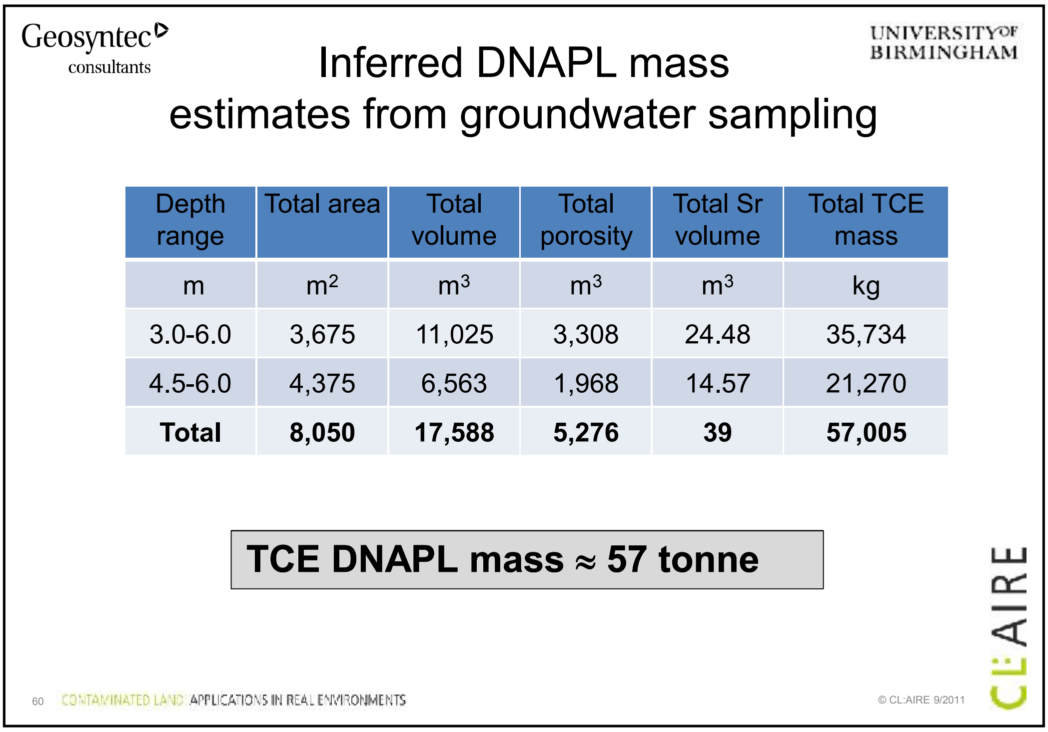

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Inferred DNAPL mass estimates from groundwater sampling

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Depth range	Total area	Total volume	Total porosity	Total Sr volume	Total TCE mass
m	m^2	m^3	m^3	m^3	kg
3.0-6.0	3,675	11,025	3,308	24.48	35,734
4.5-6.0	4,375	6,563	1,968	14.57	21,270
Total	**8,050**	**17,588**	**5,276**	**39**	**57,005**

TCE DNAPL mass ≈ 57 tonne

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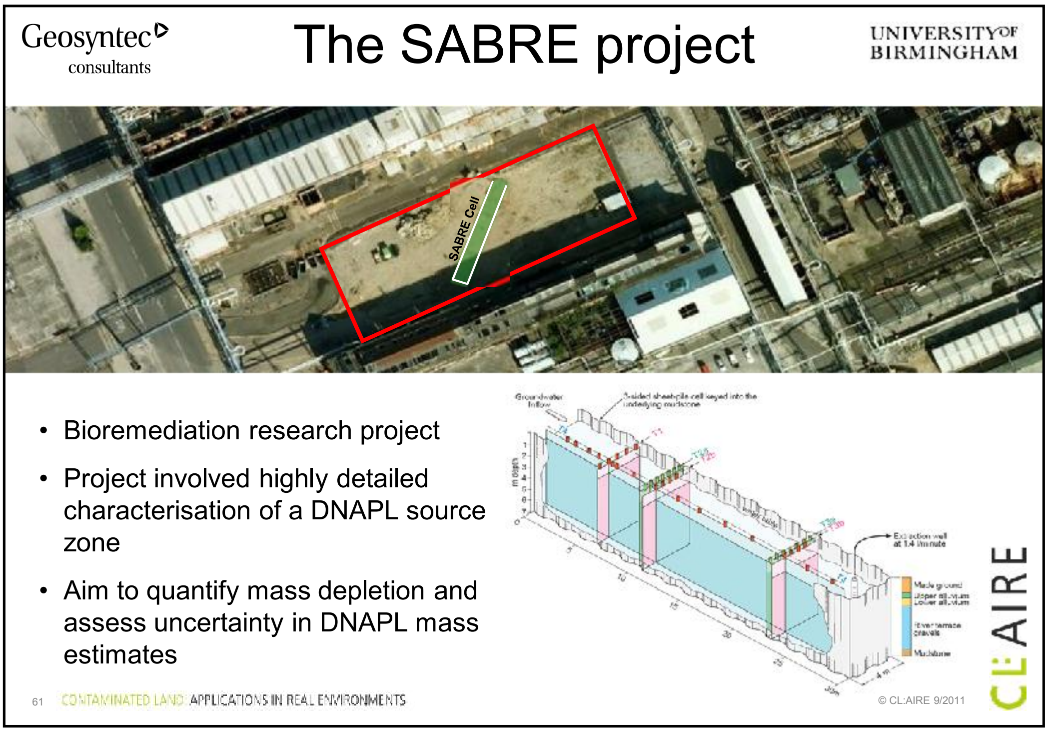

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The SABRE project

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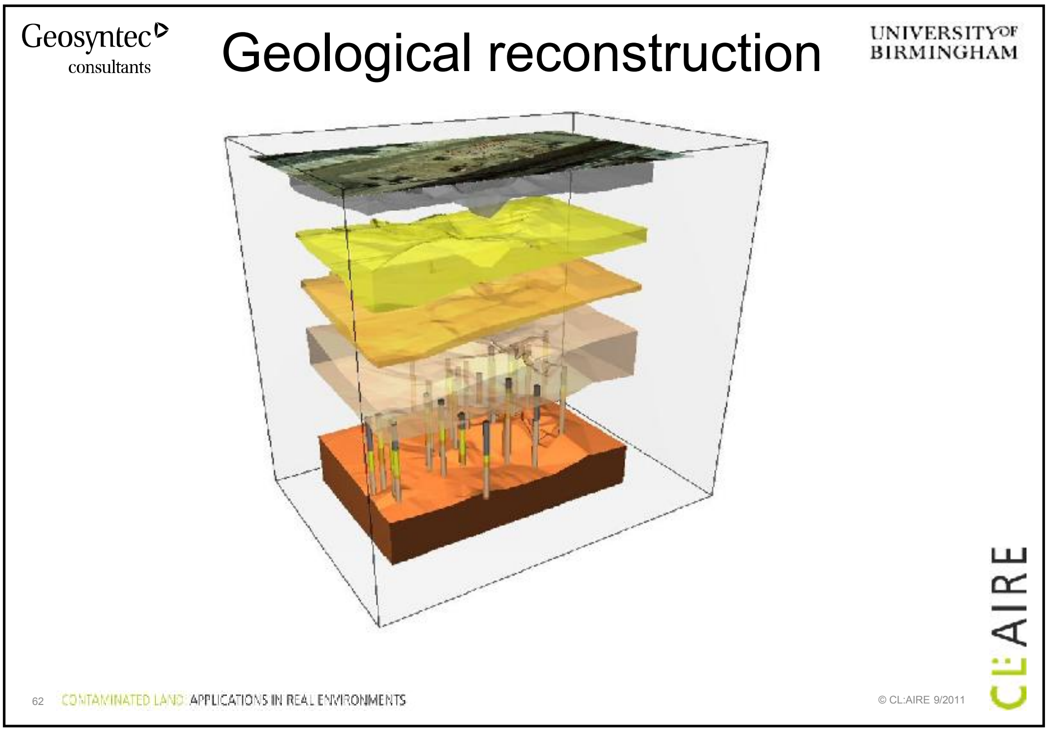
- Bioremediation research project
- Project involved highly detailed characterisation of a DNAPL source zone
- Aim to quantify mass depletion and assess uncertainty in DNAPL mass estimates



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Geological reconstruction

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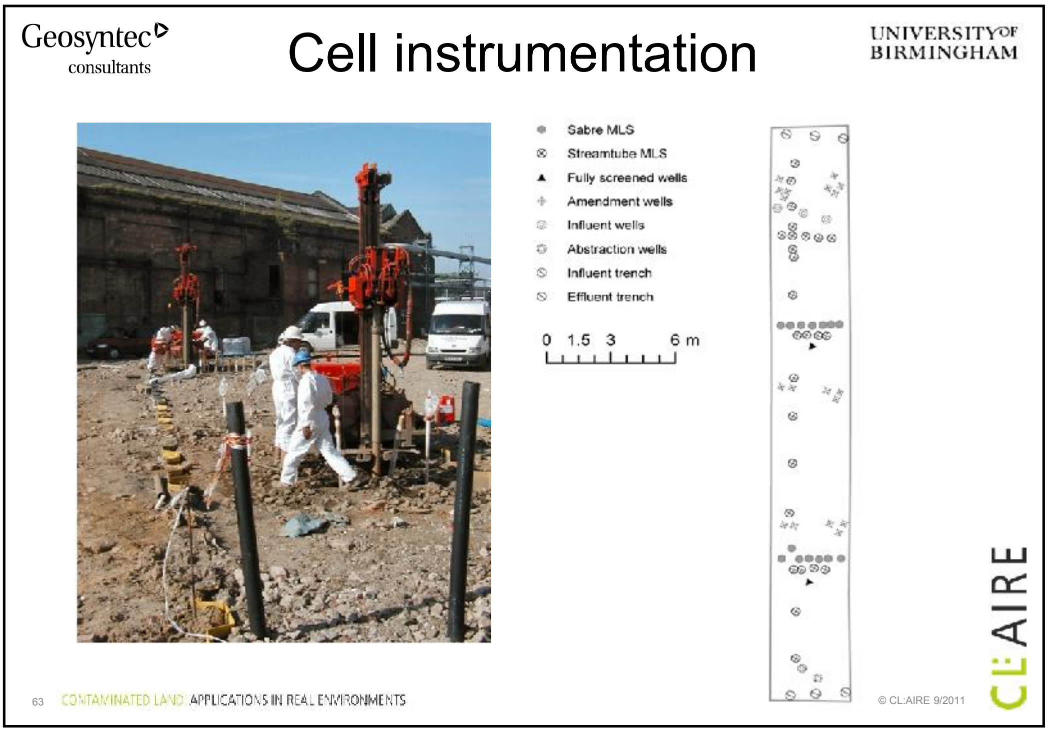
Presented by:
Dr Gary Wealthall, Geosyntec Consultants Inc. and Dr Mike Rivett, University of Birmingham



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Cell instrumentation

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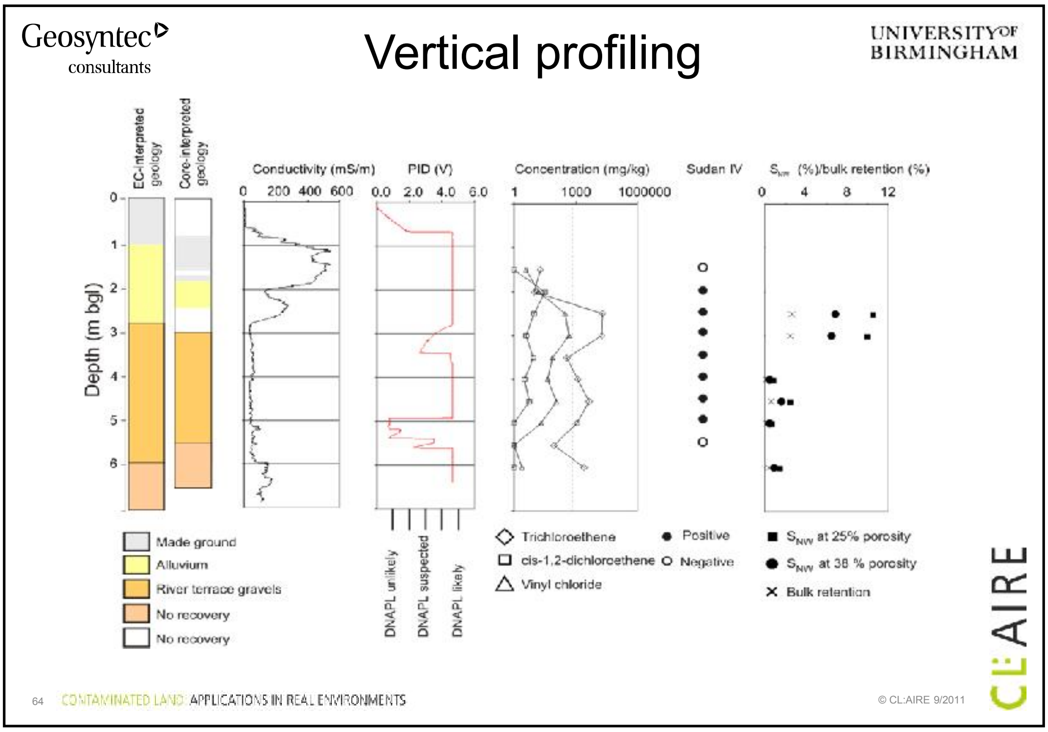

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Vertical profiling

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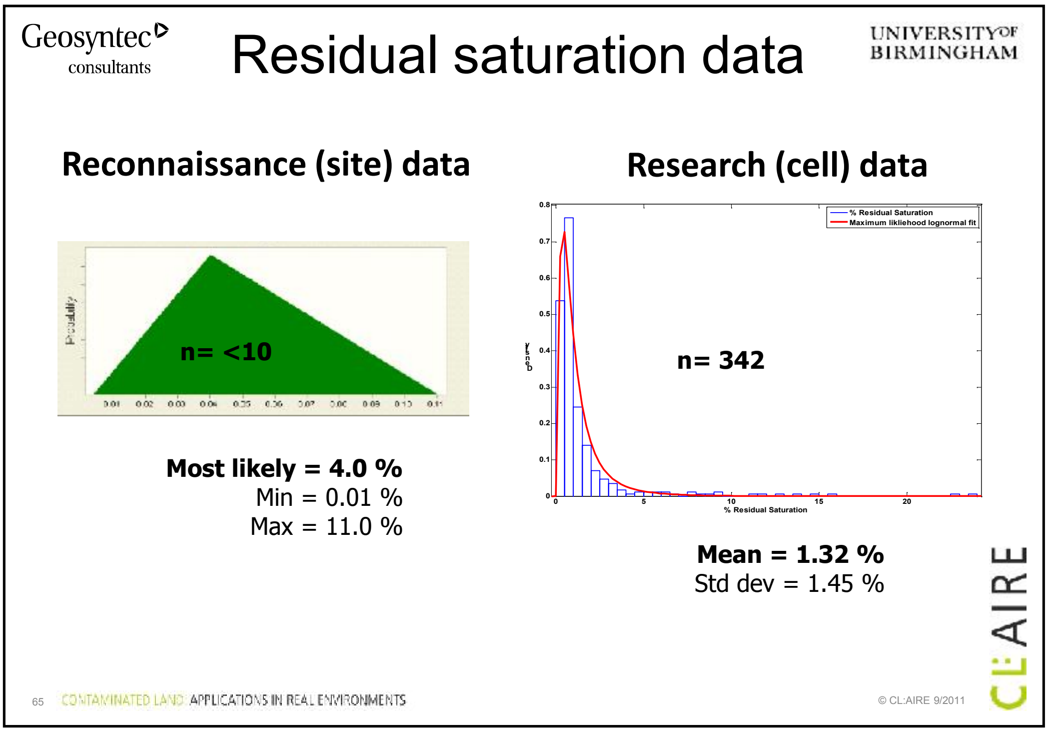

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Residual saturation data

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Reconnaissance (site) data

n= <10

Most likely = 4.0 %
Min = 0.01 %
Max = 11.0 %

Research (cell) data

n= 342

Mean = 1.32 %
Std dev = 1.45 %

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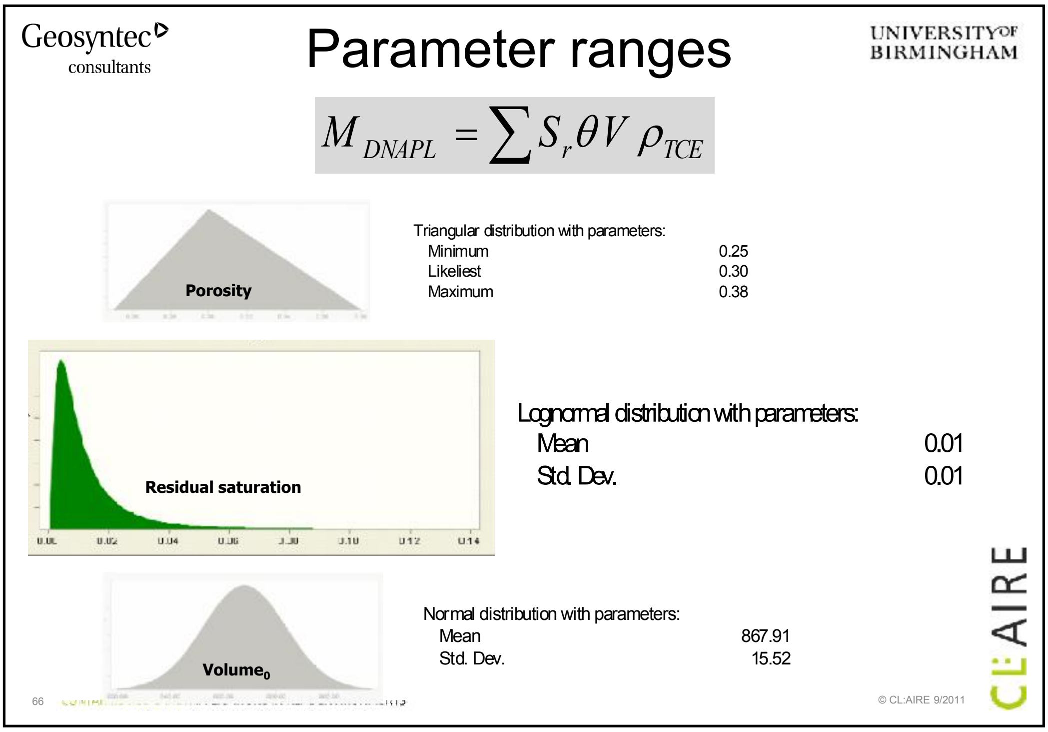

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Parameter ranges

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$$M_{DNAPL} = \sum S_r \theta V \rho_{TCE}$$

Porosity

Triangular distribution with parameters:

Minimum	0.25
Likeliest	0.30
Maximum	0.38

Residual saturation

Lognormal distribution with parameters:

Mean	0.01
Std. Dev.	0.01

$Volume_0$

Normal distribution with parameters:

Mean	867.91
Std. Dev.	15.52

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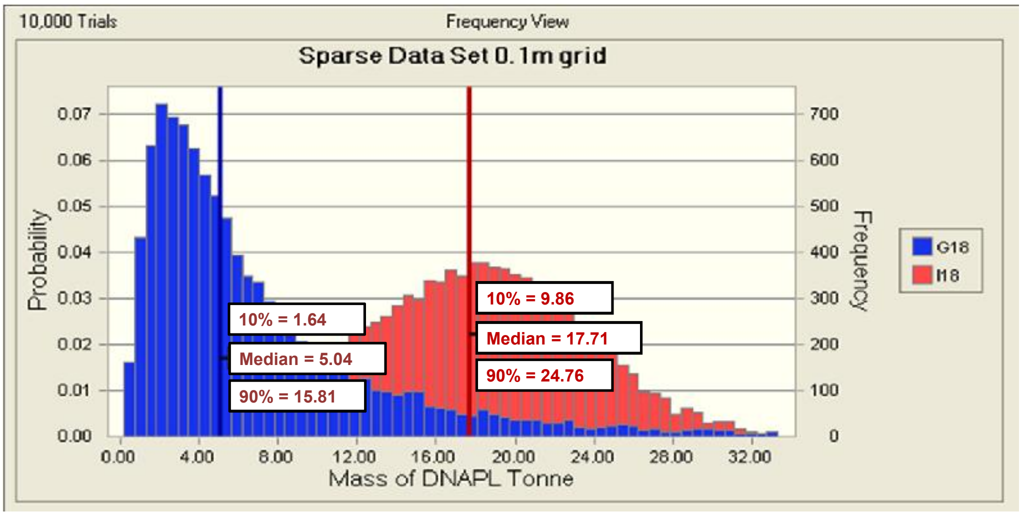
Sparse triangular versus lognormal Sr



10% = 1.64

Median = 5.04

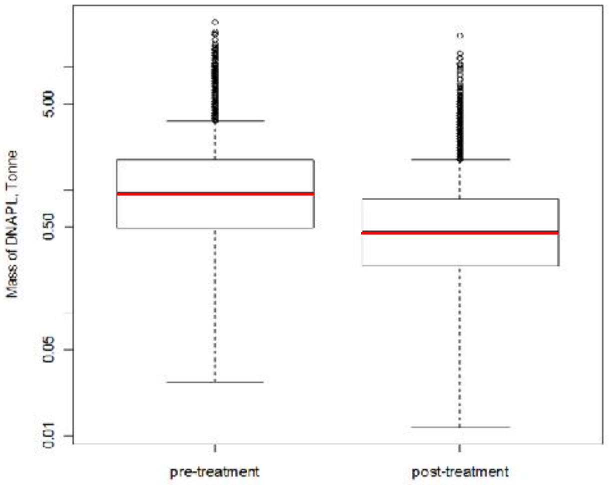
90% = 15.81

10% = 9.86

Median = 17.71

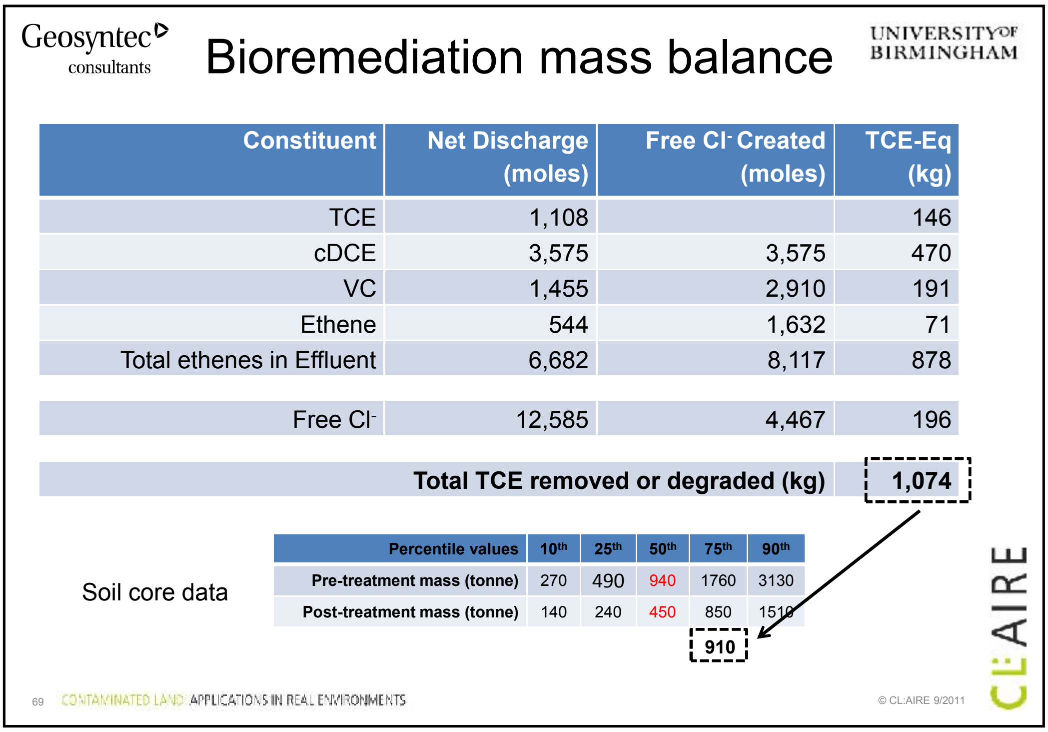
90% = 24.76

DNAPL mass comparison



Median (50th percentile) mass removal = 0.49 tonne

Percentile values	10th	25th	50th	75th	90th
Pre-treatment mass (tonne)	0.27	0.49	**0.94**	1.76	3.13
Post-treatment mass (tonne)	0.14	0.24	**0.45**	0.85	1.51



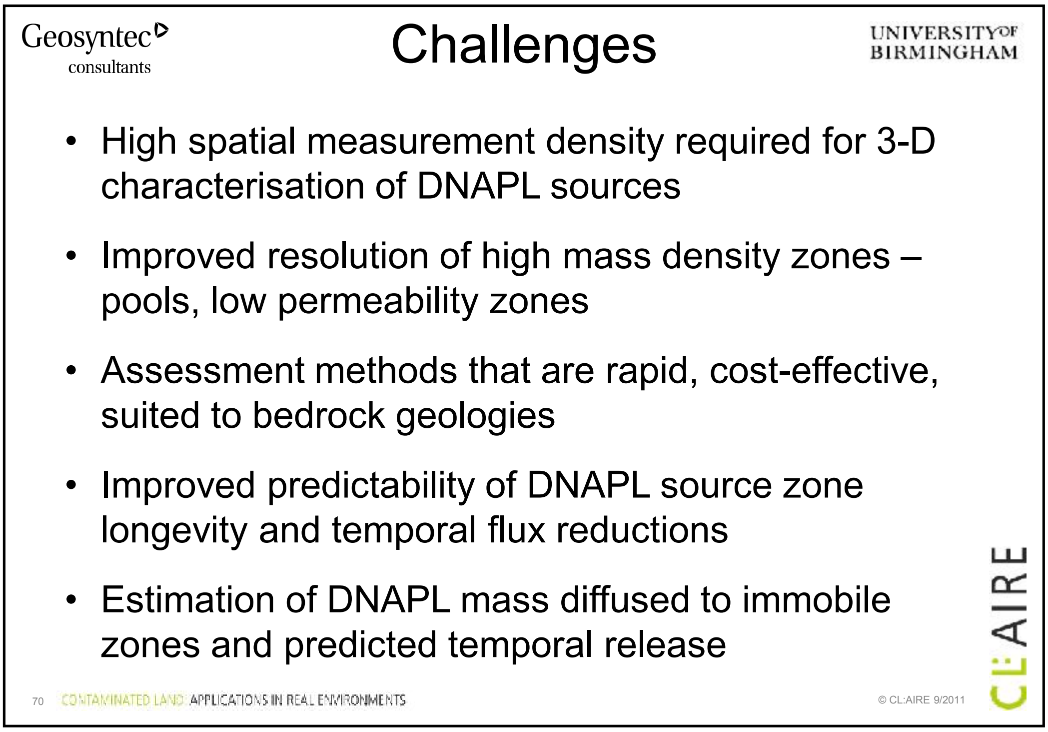
Bioremediation mass balance

Constituent	Net Discharge (moles)	Free Cl^- Created (moles)	TCE-Eq (kg)
TCE	1,108		146
cDCE	3,575	3,575	470
VC	1,455	2,910	191
Ethene	544	1,632	71
Total ethenes in Effluent	6,682	8,117	878
Free Cl^-	12,585	4,467	196
Total TCE removed or degraded (kg)			**1,074**

Soil core data

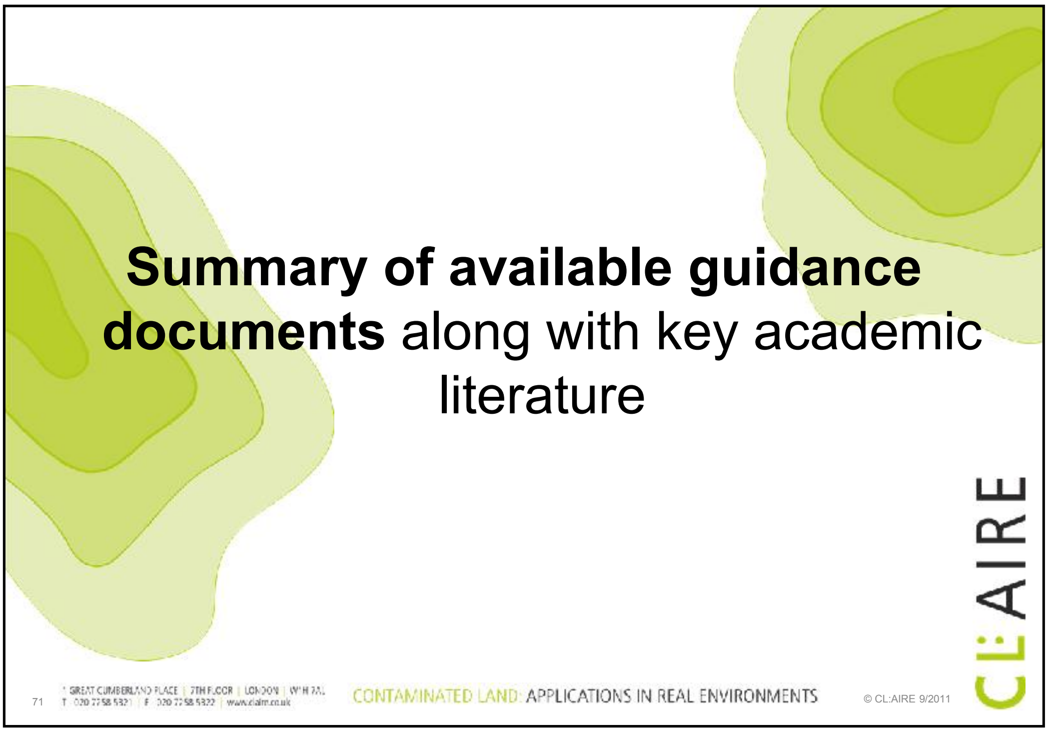
Percentile values	**10th**	**25th**	**50th**	**75th**	**90th**
Pre-treatment mass (tonne)	270	490	940	1760	3130
Post-treatment mass (tonne)	140	240	450	850	1510

910

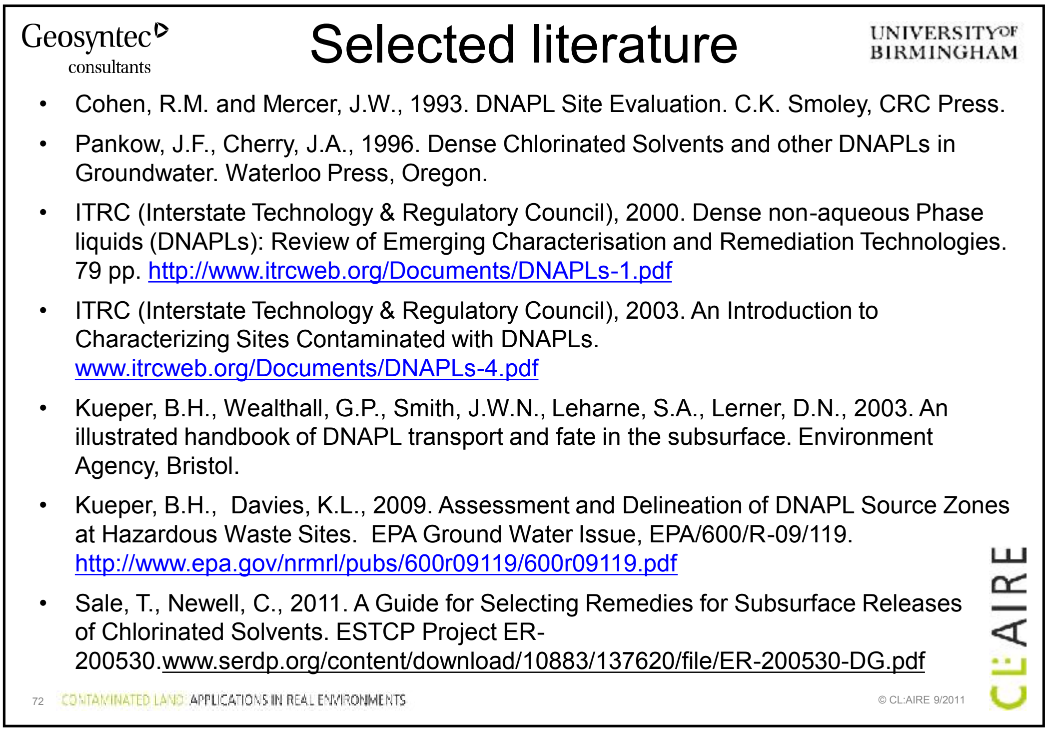


Challenges

- High spatial measurement density required for 3-D characterisation of DNAPL sources
- Improved resolution of high mass density zones – pools, low permeability zones
- Assessment methods that are rapid, cost-effective, suited to bedrock geologies
- Improved predictability of DNAPL source zone longevity and temporal flux reductions
- Estimation of DNAPL mass diffused to immobile zones and predicted temporal release



Summary of available guidance documents along with key academic literature



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Selected literature

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- Pankow, J.F., Cherry, J.A., 1996. Dense Chlorinated Solvents and other DNAPLs in Groundwater. Waterloo Press, Oregon.
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- Kueper, B.H., Wealthall, G.P., Smith, J.W.N., Leharne, S.A., Lerner, D.N., 2003. An illustrated handbook of DNAPL transport and fate in the subsurface. Environment Agency, Bristol.
- Kueper, B.H., Davies, K.L., 2009. Assessment and Delineation of DNAPL Source Zones at Hazardous Waste Sites. EPA Ground Water Issue, EPA/600/R-09/119. http://www.epa.gov/nrmrl/pubs/600r09119/600r09119.pdf
- Sale, T., Newell, C., 2011. A Guide for Selecting Remedies for Subsurface Releases of Chlorinated Solvents. ESTCP Project ER-200530.www.serdp.org/content/download/10883/137620/file/ER-200530-DG.pdf

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Useful literature listing

Cited and Useful literature listing

DNAPL Site Characterisation:
Tools and Techniques

Gary Wealthall (Geosyntec Consultants, Inc)

Mike Rivett (University of Birmingham)

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Brewster, M.L., Annan, A.P., Greenhouse, J.P., Kueper, B.H., Olhoeft, G.R., Redman, J.D., and Sander, K.A., 1995. Observed migration of a controlled DNAPL release by geophysical methods. Ground Water, 33(6), 977-987.

Brooks, M.C., Annable, M.D., Rao, P.S.C., Hatfield, K., Jawitz, J.W., Wise, W.R., Wood, A.L. and Enfield, C.G., 2002. Controlled release, blind tests of DNAPL characterization using partitioning tracers. *J. Contaminant Hydrology*, 59, 187-210.

Davis, B.M., Istok J.D., Semprini L., 2003. Static and push-pull methods using radon-222 to characterize dense nonaqueous phase liquid saturations Ground Water 41 (4), 470-481.

Chapman, S.W., Parker, B.L., 2005. Plume persistence due to aquitard back diffusion following dense nonaqueous phase liquid source removal or isolation. *Water Resources Research*, 41, W12411.

pdf available of cited useful literature

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Questions?

Please answer the five multiple-choice questions which will appear on your screen shortly so that we can gain your feedback on today's webinar.

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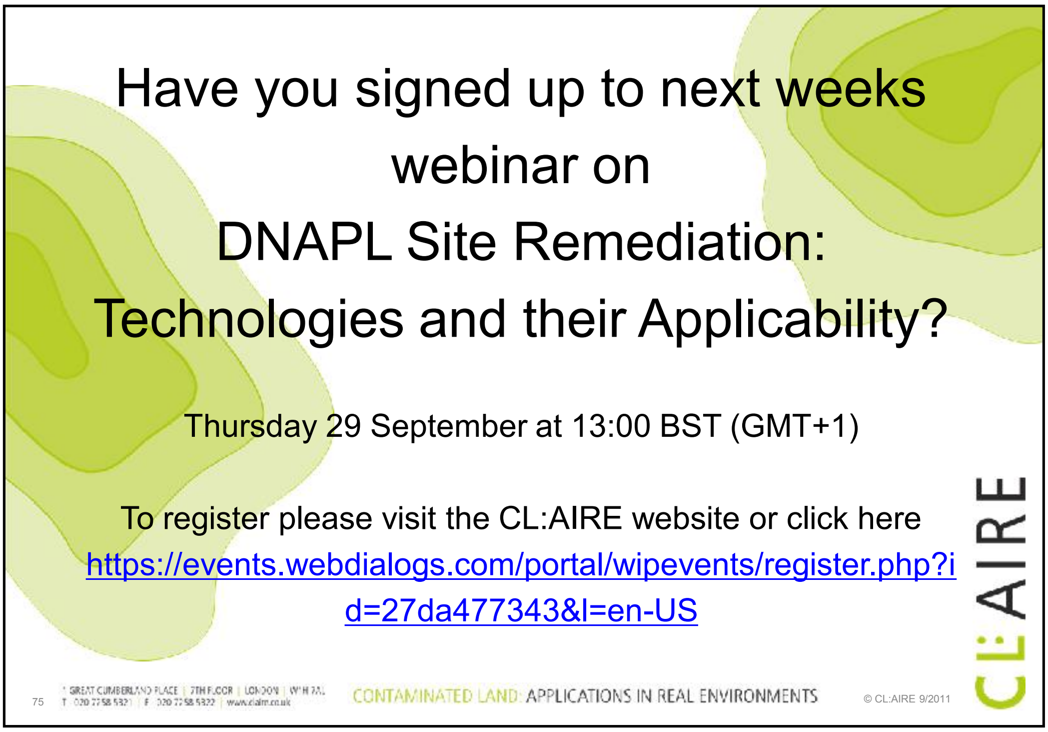

Have you signed up to next weeks webinar on DNAPL Site Remediation: Technologies and their Applicability?

Thursday 29 September at 13:00 BST (GMT+1)

To register please visit the CL:AIRE website or click here
https://events.webdialogs.com/portal/wipevents/register.php?id=27da477343&l=en-US