A review of the recent international LNAPL literature

– are we missing out on something?

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Redacted version of presentation – a few slides / images are missing; none are significant to the main messages

Keynote presentation at 'NAPL in the UK context, does it matter?' , 2019 Year of Carbon meeting of Contaminated Land Group of The Geological Society, Birmingham, 6 November, 2019

A review of the recent international LNAPL literature …

- Investigation and remediation of sites contaminated by LNAPLs remains a common concern in the UK
- However, there appears little published recent research from ‘UK authors’ supporting this effort

- It is hence a concern that our lack of substantial involvement may result in our awareness of advances in the international LNAPL literature becoming low

… are we missing out on something?

A ‘light-touch review’

- ‘Light-touch review’ of the international LNAPL literature published in the 2010-19 decade to examine specific LNAPL sub-topics of interest
- But, also assessing numbers of LNAPL publications before 2010 to see how modern numbers compare
- Searching on the topic ‘LNAPL’ is not a perfect barometer of modern activity, however,
- the uniqueness of the LNAPL acronym to our contaminated land/groundwater industry is helpful

Topic search on ‘LNAPL’

- Searched on ‘LNAPL’ as a ‘Topic’ within the **Web of Science** scientific literature database

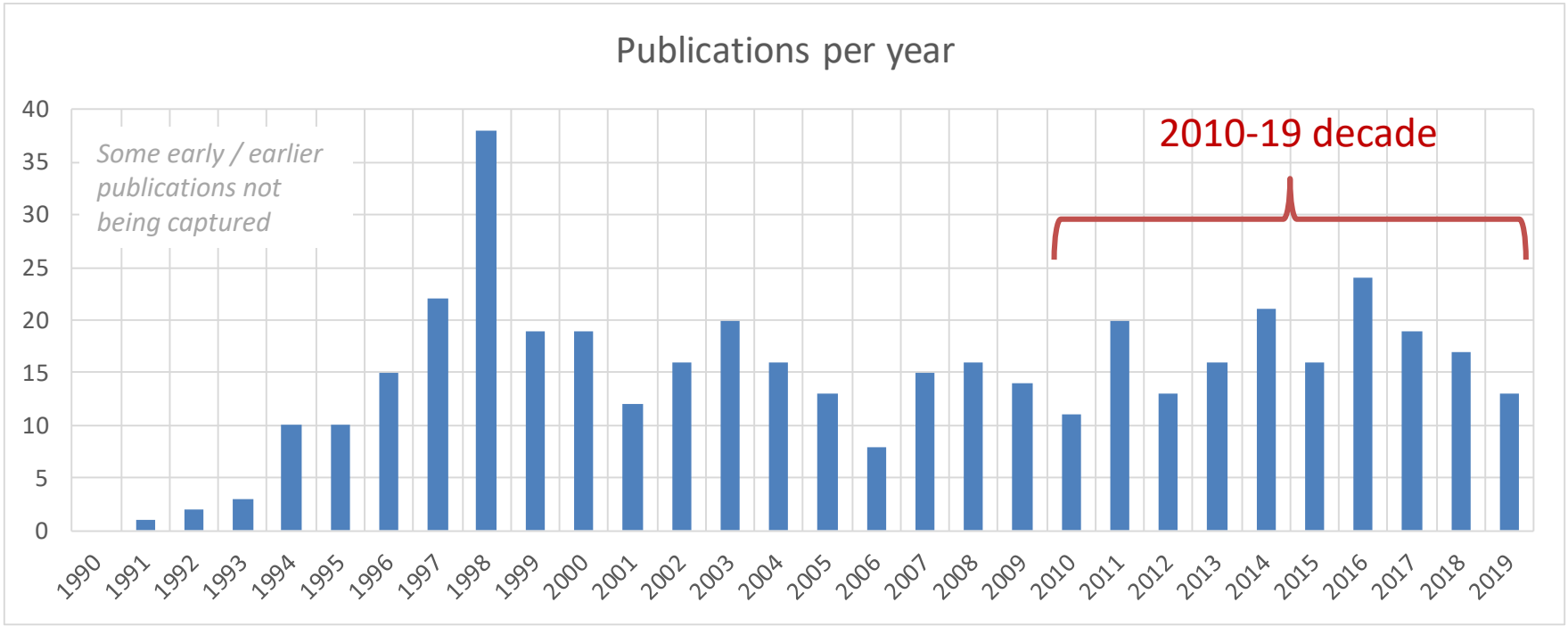
- ‘Topic’ searches the following fields: Title, Abstract, Author Keywords, Keywords Plus® (≥ 2 mentions in reference list)
- *Recognising,* no mention of LNAPL in these = NO chance of paper being found
- *Recognising,* NAPL was first coined as a term in 1981 at a site in Niagara Falls, New York
- *Recognising,* groundwater H/C pollution research dates back to 1960s, well before NAPLs were invented
- Hence, work herein is indicative of research activity

Web of Science ‘LNAPL’ topic search

Download: 28/6/2019

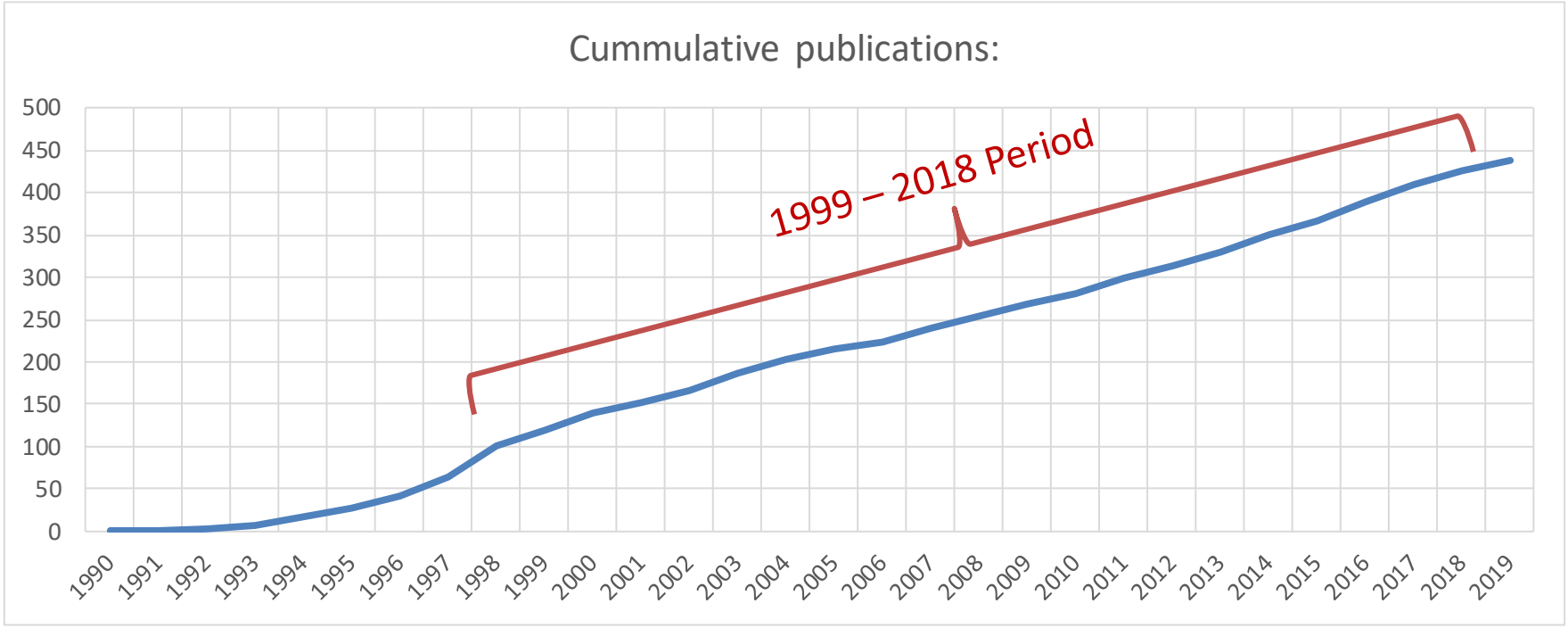
Timespan=All years. Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.

- 439 LNAPL publications since 1990
- (Compared to 1361 DNAPL publications)
- 170 LNAPL publications 2010 – 19 (39 %)



Web of Science ‘LNAPL’ topic search

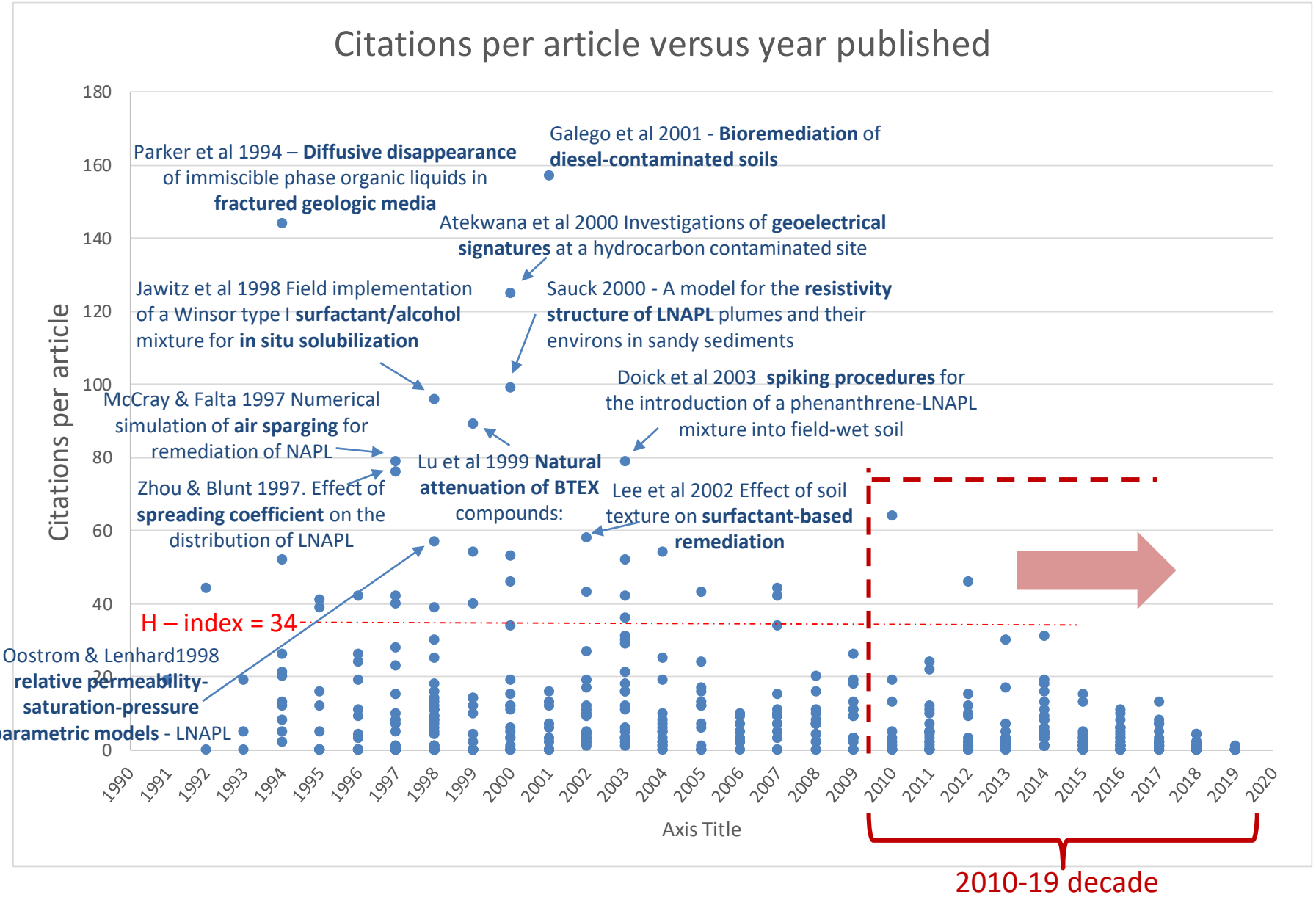
- 1999 – 2018 linear growth in LNAPL publications
- Period mean = 16.3 ± 3.7 publications per annum



‘Prof LNAPL’ citation metrics

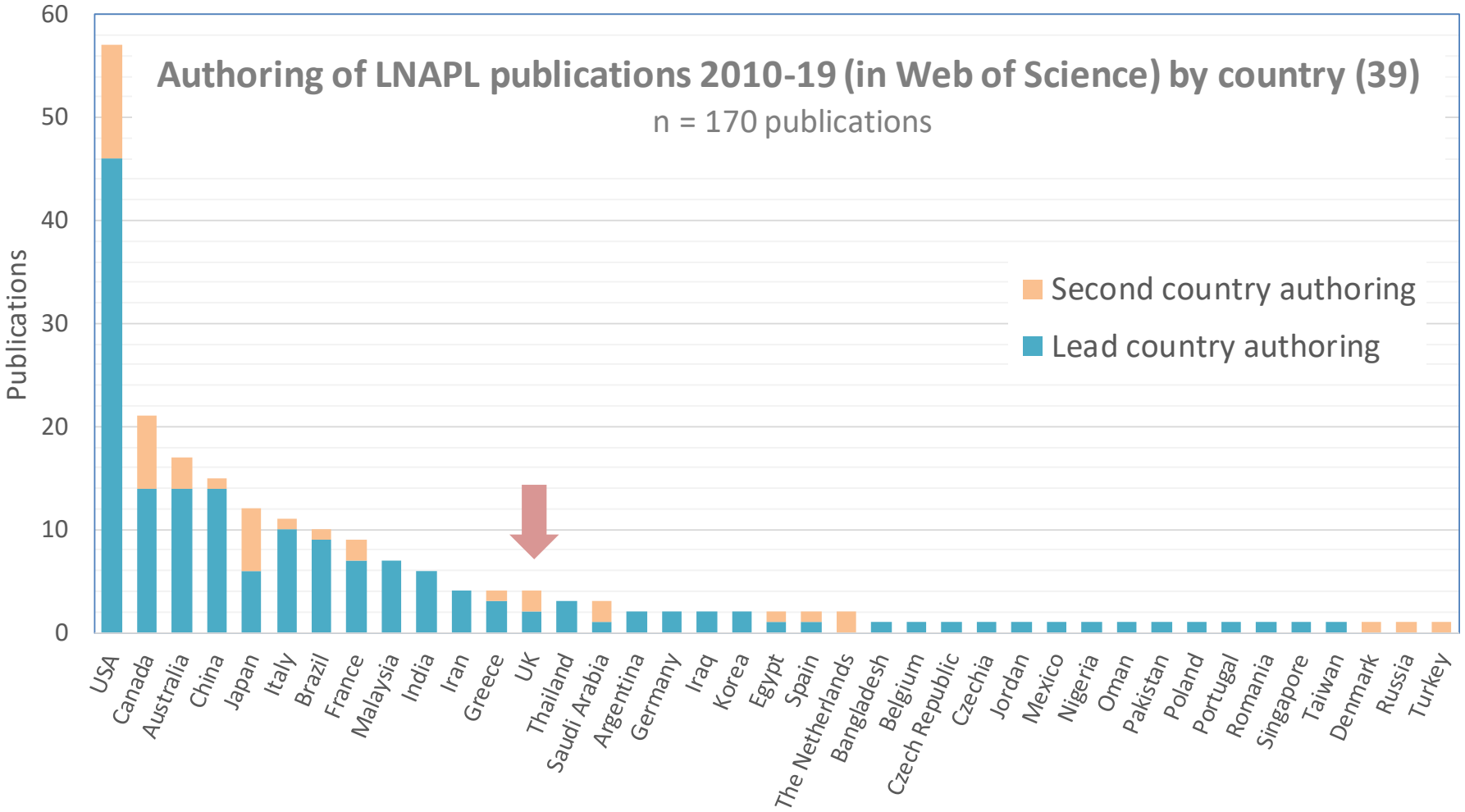
- 439 LNAPL publications to date
- Received a total of 4496 citations to date
- Average citation (times cited) per paper = 10.2
- H-index = 34 (this means that 34 of the papers have received at least 34 citations)
- Most cited LNAPL paper: 157 citations
  - Gallego et al. (2001). Bioremediation of diesel-contaminated soils: Evaluation of potential in situ techniques by study of bacterial degradation. Bioremediation, 12(5), 325-35. https://doi.org/10.1023/A:1014397732435
  - This paper also has the maximum citations per year average at 8.7 citations per year

Some well cited articles (n = 439 publications)



2010-19 decade of LNAPL publications

Authoring countries



- 75 % are single country authored publications
- 25 % are international collaborations

UK LNAPL contribution 2010-19:

- UK lead authored publications = 2
- UK supporting (2nd author country) publications = 2
- UK total = 4 / 170 publications = 2.4 % of global effort

Thornton, S.F., Tobin, K. and Smith, J.W., 2013. Comparison of Constant and Transient-Source Zones on Simulated Contaminant Plume Evolution in Groundwater: Implications for Hydrogeological Risk Assessment. *Groundwater Monitoring & Remediation*, *33*(3), pp.78-91.

Tomlinson, D., Rivett, M.O., Wealthall, G.P., Sweeney, R., 2017. Understanding complex LNAPL sites: Illustrated handbook of LNAPL transport and fate in the subsurface. *Journal of Environmental Management*, 204, 748-756 https://doi.org/10.1016/j.jenvman.2017.08.015

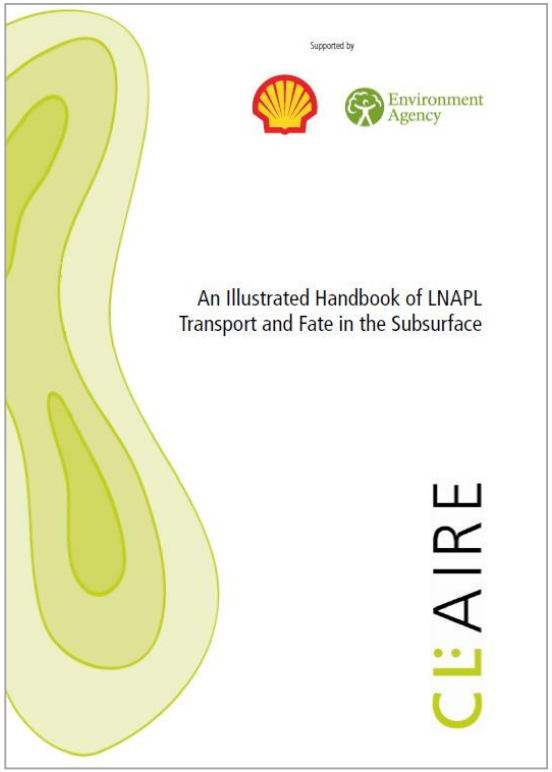
Benbow, S.J., Rivett, M.O., Chittenden, N., Herbert, A.W., Watson, S, Williams, S.J., Norris, S., 2014. Potential migration of buoyant LNAPL from Intermediate Level Waste (ILW) emplaced in a Geological Disposal Facility (GDF) for UK radioactive waste. *Journal of Contaminant Hydrology, 167, 1 – 22.* *http://dx.doi.org/10.1016/j.jconhyd.2014.07.011* [Open access]

Rahman, N.A., Foong, L.K., Lewis, R.W. and Nazir, R., 2018. Laboratory investigation of LNAPL migration in double-porosity soil under fractured condition using digital image analysis. *Transport in Porous Media*, *125*(3), pp.521-542.

Some other UK contributions

(not captured in Web of Science LNAPL search)

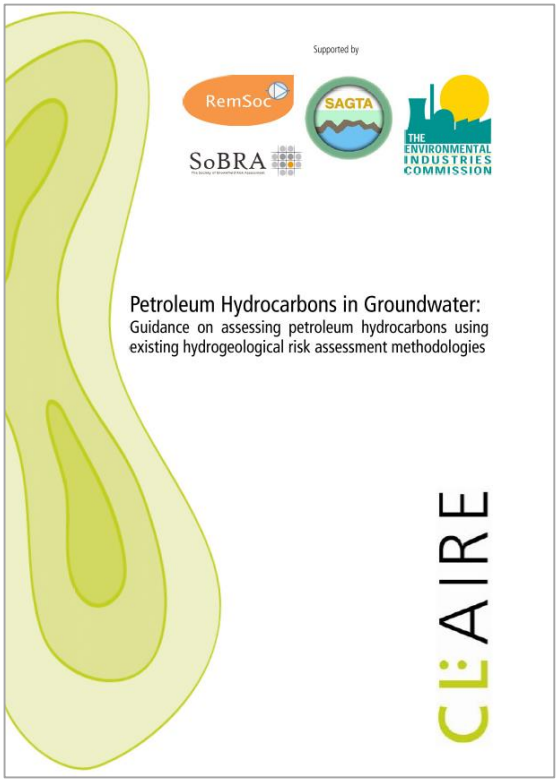
2014 LNAPL handbook



7500 downloads *

www.claire.co.uk/LNAPL

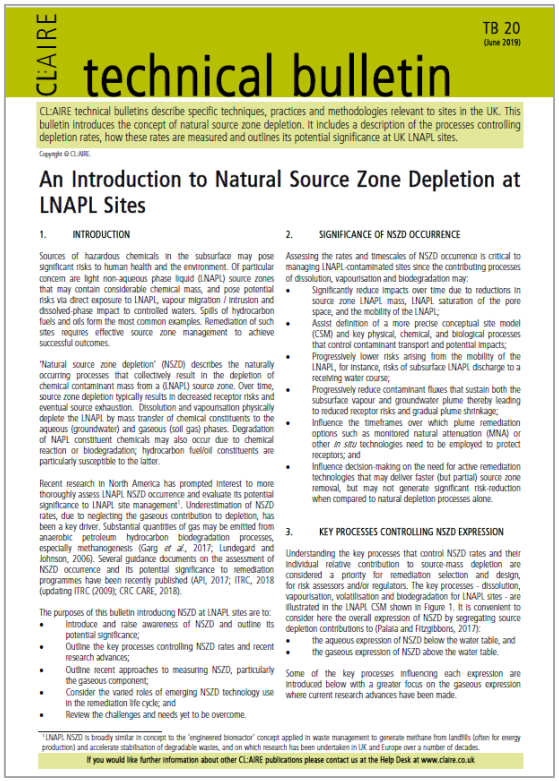
2017 Pet. H/C guidance



22000 downloads

https://www.claire.co.uk/phg .

2019 NSZD Bulletin


CL:AIRE technical bulletin TB 20 (June 2019)

CL:AIRE technical bulletins describe specific techniques, practices and methodologies relevant to sites in the UK. This bulletin introduces the concept of natural source zone depletion. It includes a description of the processes controlling depletion rates, how these rates are measured and outlines its potential significance at UK LNAPL sites.

An Introduction to Natural Source Zone Depletion at LNAPL Sites

1. INTRODUCTION

Sources of hazardous chemicals in the subsurface may pose significant risks to human health and the environment. Of particular concern are light non-aqueous phase liquid (LNAPL) source zones that may contain considerable chemical mass, and pose potential risks via direct exposure to LNAPL, vapour migration / intrusion and dissolved-phase impact to controlled waters. Spills of hydrocarbon fuels and oils form the most common examples. Remediation of such sites requires effective source zone management to achieve successful outcomes.

'Natural source zone depletion' (NSZD) describes the naturally occurring processes that collectively result in the depletion of chemical contaminant mass from a (LNAPL) source zone. Over time, source zone depletion typically results in decreased receptor risks and eventual source exhaustion. Dissolution and vapourisation physically deplete the LNAPL by mass transfer of chemical constituents to the aqueous (groundwater) and gaseous (soil gas) phases. Degradation of NAPL constituent chemicals may also occur due to chemical reaction or biodegradation; hydrocarbon fuel/oil constituents are particularly susceptible to the latter.

Recent research in North America has prompted interest to more thoroughly assess LNAPL NSZD occurrence and evaluate its potential significance to LNAPL site management[1]. Underestimation of NSZD rates, due to neglecting the gaseous contribution to depletion, has been a key driver. Substantial quantities of gas may be emitted from anaerobic petroleum hydrocarbon biodegradation processes, especially methanogenesis (Garg *et al.*, 2017; Lundegard and Johnson, 2006). Several guidance documents on the assessment of NSZD occurrence and its potential significance to remediation programmes have been recently published (API, 2017; ITRC, 2018 (updating ITRC (2009); CRC CARE, 2018).

The purposes of this bulletin introducing NSZD at LNAPL sites are to:

- Introduce and raise awareness of NSZD and outline its potential significance;
- Outline the key processes controlling NSZD rates and recent research advances;
- Outline recent approaches to measuring NSZD, particularly the gaseous component;
- Consider the varied roles of emerging NSZD technology use in the remediation life cycle; and
- Review the challenges and needs yet to be overcome.

2. SIGNIFICANCE OF NSZD OCCURRENCE

Assessing the rates and timescales of NSZD occurrence is critical to managing LNAPL-contaminated sites since the contributing processes of dissolution, vapourisation and biodegradation may:

- Significantly reduce impacts over time due to reductions in source zone LNAPL mass, LNAPL saturation of the pore space, and the mobility of the LNAPL;
- Assist definition of a more precise conceptual site model (CSM) and key physical, chemical, and biological processes that control contaminant transport and potential impacts;
- Progressively lower risks arising from the mobility of the LNAPL, for instance, risks of subsurface LNAPL discharge to a receiving water course;
- Progressively reduce contaminant fluxes that sustain both the subsurface vapour and groundwater plume thereby leading to reduced receptor risks and gradual plume shrinkage;
- Influence the timeframes over which plume remediation options such as monitored natural attenuation (MNA) or other *in situ* technologies need to be employed to protect receptors; and
- Influence decision-making on the need for active remediation technologies that may deliver faster (but partial) source zone removal, but may not generate significant risk-reduction when compared to natural depletion processes alone.

3. KEY PROCESSES CONTROLLING NSZD EXPRESSION

Understanding the key processes that control NSZD rates and their individual relative contribution to source-mass depletion are considered a priority for remediation selection and design, for risk assessors and/or regulators. The key processes - dissolution, vapourisation, volatilisation and biodegradation for LNAPL sites - are illustrated in the LNAPL CSM shown in Figure 1. It is convenient to consider here the overall expression of NSZD by segregating source depletion contributions to (Palaia and Fitzgibbons, 2017):

- the aqueous expression of NSZD below the water table, and
- the gaseous expression of NSZD above the water table.

Some of the key processes influencing each expression are introduced below with a greater focus on the gaseous expression where current research advances have been made.

[1] LNAPL NSZD is broadly similar in concept to the 'engineered bioreactor' concept applied in waste management to generate methane from landfills (often for energy production) and accelerate stabilisation of degradable wastes, and on which research has been undertaken in UK and Europe over a number of decades.

If you would like further information about other CL:AIRE publications please contact us at the Help Desk at www.claire.co.uk

https://www.claire.co.uk/component/phocadownload/category/17-technical-bulletins?download=681:tb-20-an-introduction-to-natural-source-zone-depletion-at-lnapl-sites

1500 downloads

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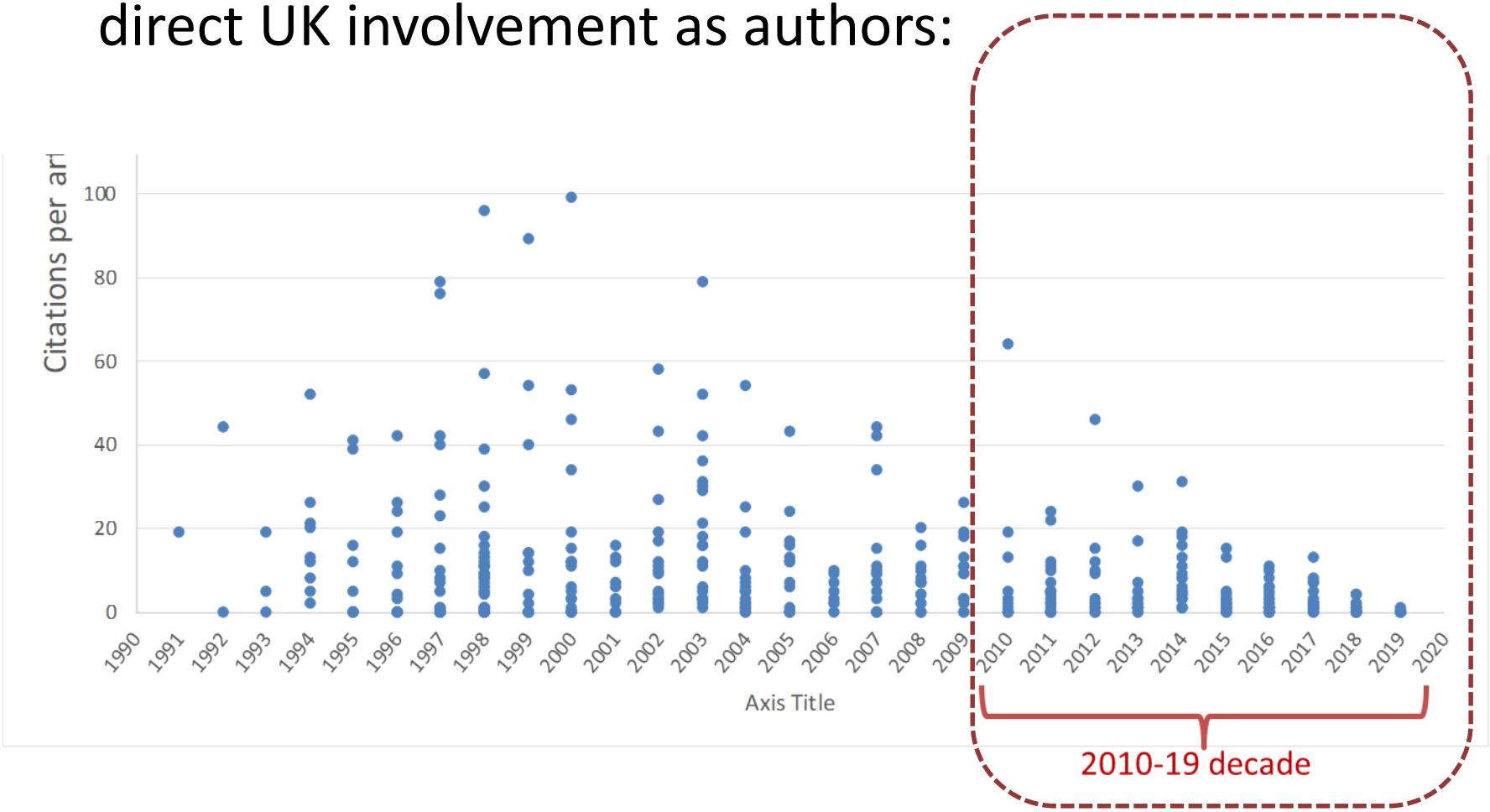
* As of 5 Nov 2019

So, what are we missing out on?

- 166 / 170 LNAPL publications in 2010-19 without direct UK involvement as authors:



Where is it published?

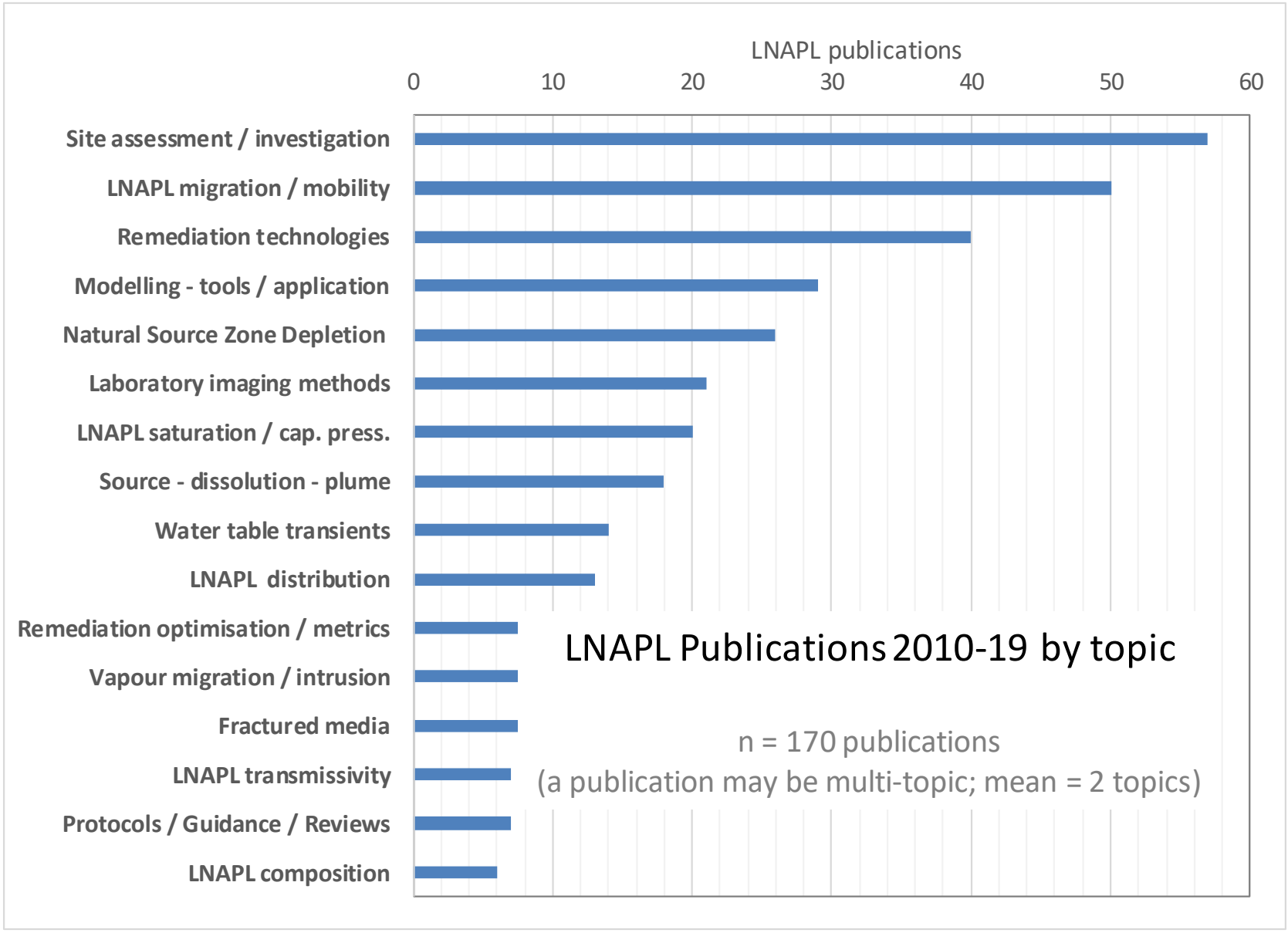
- 170 articles in 85 different journals/outlets!

Publications	JOURNAL
19	GROUND WATER MONITORING AND REMEDIATION
16	JOURNAL OF CONTAMINANT HYDROLOGY
6	GROUNDWATER
6	JOURNAL OF HAZARDOUS MATERIALS
4	COLD REGIONS SCIENCE AND TECHNOLOGY
4	JOURNAL OF APPLIED GEOPHYSICS
4	JOURNAL OF ENVIRONMENTAL MANAGEMENT
4	SOIL & SEDIMENT CONTAMINATION
4	TRANSPORT IN POROUS MEDIA
3	ENVIRONMENTAL EARTH SCIENCES
3	ENVIRONMENTAL FORENSICS
3	ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH
3	GEOTECHNICAL TESTING JOURNAL
3	JOURNAL OF ENVIRONMENTAL ENGINEERING
3	JOURNAL OF SOILS AND SEDIMENTS
3	CLEANUP COSTS TECHNOLOGIES & TECHNIQUES
3	WATER AIR AND SOIL POLLUTION
3	WATER RESOURCES RESEARCH
2	ADVANCES IN WATER RESOURCES
2	CANADIAN GEOTECHNICAL JOURNAL
2	ENVIRONMENTAL SCIENCE & TECHNOLOGY

… missing the middle order …

1	JOURNAL OF PETROLEUM SCIENCE AND ENGINEERING
1	JURNAL TEKNOLOGI
1	KARST GROUNDWATER CONTAMINATION AND PUBLIC HEALTH: BEYOND CASE STUDIES
1	NEAR SURFACE GEOPHYSICS
1	PHYSICS AND CHEMISTRY OF THE EARTH
1	POROUS MEDIA AND ITS APPLICATIONS IN SCIENCE, ENGINEERING, AND INDUSTRY
1	PROCEEDINGS OF THE XVIII INTERNATIONAL CONFERENCE ON COMPUTATIONAL METHODS IN WATER RESOURCES (CMWR 2010)
1	**QUARTERLY JOURNAL OF ENGINEERING GEOLOGY AND HYDROGEOLOGY**
1	RENDICONTI ONLINE SOCIETA GEOLOGICA ITALIANA
1	SAINS MALAYSIANA
1	SCIENCEASIA
1	SOILS AND FOUNDATIONS
1	SPECIAL TOPICS & REVIEWS IN POROUS MEDIA-AN INTERNATIONAL JOURNAL
1	STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT
1	SURVEYS IN GEOPHYSICS
1	SUSTAINABILITY
1	WATER RESEARCH
1	WATER SCIENCE AND TECHNOLOGY

LNAPL Publications by topic (2010-19)



LNAPL - Site assessment / investigation

- 57 publications, with breakdown to:

Sub-topic	Site Assessment (abreviated publication title)	Authors	Author - country 1	Source Title	Citations
Biogeochem	Geochemical controls on secondary water quality impacts - Bimidji	Ng, G. -H. Cry	USA	JOURNAL OF CONTAMINANT HY DR	19
Biogeochem	Baterial communities in LNAPL body	Irianni-Renno, I	USA	APPLIED MICROBIOLOGY AND BIOT	4
Biogeochem	In-situ biodeg of MTBE via CSIA	Lu, Jun; Muran	USA	GROUND WATER MONITORING ANE	0
Fingerprint - composition	Field screening - bubbling extraction PID for Benz - VOCs	Devine, Catalin	USA	GROUND WATER MONITORING ANE	3
Fingerprint - composition	LNAPL stability via mass balance approach	Mahler, Nichol	USA	GROUND WATER	2
Fingerprint - composition	Chemical fingerprinting to enhance remedial SI	Lu, Jun	USA	ENVIRONMENTAL FORENSICS	1
Fingerprint - composition	Act. Carbon for water and non-volatile determination	Batkova, Kami	Czechia	SOIL AND WATER RESEARCH	1
Fingerprint - composition	Monitoring composition	Frollini, Eleonc	Italy	RENDICONTI ONLINE SOCIETA GEOI	0
Fingerprint - composition	Non-volatile LNAPL content	Teressa Chala	Czech Republic	SOIL AND WATER RESEARCH	0
Fingerprint - composition	LNAPL leaching and migration case	Cioban, Tiberiu	Romania	ECOLOGY, ECONOMICS, EDUCATIC	0

LNAPL - Site assessment / investigation … continued

Sub-topic	Site Assessment (abreviated publication title)	Authors	Author - country 1	Source Title	Citations
LNAPL Vol. Distrib. Mob.	Tool to estimate LNAPL distrib and T - using histori/current fluid levels	Lenhard, R. J.;	Australia	JOURNAL OF CONTAMINANT HYDR	7
LNAPL Vol. Distrib. Mob.	Cryogenic coring	Kiaalhosseini,	USA	GROUND WATER MONITORING AND	6
LNAPL Vol. Distrib. Mob.	Urban coast oil spill case	Nambi, Induma	India	ENVIRONMENTAL MONITORING AND	3
LNAPL Vol. Distrib. Mob.	Identification of confined / perched LNAPL	Kirkman, Andr	USA	GROUND WATER MONITORING AND	3
LNAPL Vol. Distrib. Mob.	Probabilistic data integration to chracterise spatial residual distribution	Hosseini, Amir	Canada	STOCHASTIC ENVIRONMENTAL RES	3
LNAPL Vol. Distrib. Mob.	Bail-down test - lab scale	Palmier, Cedri	France	TRANSPORT IN POROUS MEDIA	2
LNAPL Vol. Distrib. Mob.	LNAPL Transmissivity: A Twisted Parameter	Beckett, G. D.	USA	GROUND WATER MONITORING AND	2
LNAPL Vol. Distrib. Mob.	Refinement of Bouwer-Rice Baildown Test Analysi	Kirkman, Andr	USA	GROUND WATER MONITORING AND	2
LNAPL Vol. Distrib. Mob.	Baildown tests	Ahmed, Waqa	Pakistan	ARABIAN JOURNAL FOR SCIENCE A	0
LNAPL Vol. Distrib. Mob.	LNAPL volumes in Heterogeneous media	Alfaro Soto, Mi	Brazil	JOURNAL OF ENVIRONMENTAL MA	0
LNAPL Vol. Distrib. Mob.	Photo logging UV fluorescence profiling tool	McCall, Wesle	USA	ENVIRONMENTAL EARTH SCIENCES	0
LNAPL Vol. Distrib. Mob.	Recoverable LNAPL vol estimations	Frollini, Eleonc	Italy	ACQUE SOTTERRANEE-ITALIAN JO	0
LNAPL Vol. Distrib. Mob.	Specific volume via apparent thickness	de Souza, Mic	Brazil	ENGENHARIA SANITARIA E AMBIEN	0

LNAPL Site assessment / investigation … continued

Sub-topic	Site Assessment (abreviated publication title)	Authors	Author - country 1	Source Title	Citations
Tracers	LNAPL flux via single well mixing tracer dilution tests - 7 field sites	Mahler, Nichol	USA	GROUND WATER	3
Tracers	Radon as natural tracer of oil recovery	Ponsin, Violair	France	GROUND WATER MONITORING AND	2
Tracers	LNAPL flux via single well mixing tracer dilution tests	Smith, Tim; Sa	USA	GROUND WATER	2
Tracers	Single well LNAPL tracer tests	Pennington, Ar	USA	GROUND WATER MONITORING AND	1
Tracers	Field tracer test for design of NNAPL surfactant flushing	Robert, Thoma	Canada	GROUND WATER MONITORING AND	1
Tracers	Source determination via Trimethylpentane tracers	Vaezihir, Abdo	Iran	ENVIRONMENTAL FORENSICS	1
Tracers	Rn-222 profiles	Cohen, Gregor	France	SCIENCE OF THE TOTAL ENVIRONM	0
Tracers	Hydrogeol beads floatingtracers	Vesper, Dorotl	USA	KARST GROUNDWATER CONTAMIN	0
Tracers	Single well tracer dilution to evaluate LNAPL flux	Lago, Gabriel F	Australia	GROUNDWATER	0
Tracers	Single well tracer dilution to evaluate LNAPL flux	Sale, Tom; Ma	USA	GROUNDWATER	0
Tracers	Soil OC effect on fuel quantification via partitioning tracers	Rhee, Sungsu;	Korea	JOURNAL OF HAZARDOUS MATERI	0
Vapour - NSZD	Natural losses of LNAPL measured vi CO2 traps	McCoy, Kevin;	USA	GROUNDWATER	15
Vapour - NSZD	Vapor attenuation at pet. HC sites - site screening	McHugh, Thom	USA	SOIL & SEDIMENT CONTAMINATION	13
Vapour - NSZD	Delineation of LNAPL source via soil gas	Cohen, Gregor	France	JOURNAL OF CONTAMINANT HYDR	5
Vapour - NSZD	VI vertical dist screening model	Lahvis, Matthe	USA	QUARTERLY JOURNAL OF ENGINEE	2
Vapour - NSZD	Modelling of sampling soil gas in monitoring wells across water table	Lari, Kaveh So	Australia	JOURNAL OF HAZARDOUS MATERI	2
Vapour - NSZD	Vapor sampling GW wells across WT	Sweeney, Rob	USA	GROUND WATER MONITORING AND	1

LNAPL - site assessment / investigation … Geophysics 17 of 57 publications

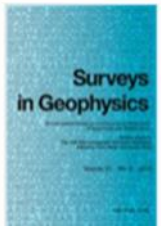
Sub-topic	Site Assessment (abreviated publication title)	Authors	Author - country 1	Source Title	Citations
Geophysics	Review - geophysical signatures of microbial activity at HC sites	Atekwana, Est	USA	SURVEYS IN GEOPHYSICS	64
Geophysics	Spectral induced polarisation imaging - former hydrogenation plant	Orozco, Adriar	Germany	JOURNAL OF CONTAMINANT HYDR	46
Geophysics	GPR 4D monitoring of spill	Bertolla, Lucia	Brazil	JOURNAL OF APPLIED GEOPHYSICS	9
Geophysics	Resistivity versus IP	Ntarlagiannis,	USA	JOURNAL OF APPLIED GEOPHYSICS	8
Geophysics	microwave tomography enhanced GPR surveys	Catapano, Ilari	Italy	JOURNAL OF APPLIED GEOPHYSICS	6
Geophysics	GPR passive inferometry - LNAPL model monitoring	Li, Jing; Zeng,	China	GEOPHYSICAL JOURNAL INTERNAT	3
Geophysics	Geohpysical, geochem - microbiol integarted characterisation aged source	Arato, Alessan	Italy	ENVIRONMENTAL SCIENCE AND PO	3
Geophysics	Detecting LNAPL via electrical rsistivity	Halihan, Todd;	USA	JOURNAL OF CONTAMINANT HYDR	2
Geophysics	GPR detection of LNAPLs	Lu, Qi; Feng, X	China	2011 IEEE INTERNATIONAL GEOSCI	2
Geophysics	NMR logging	Spurlin, Matthe	USA	REMEDIATION-THE JOURNAL OF EN	0
Geophysics	Hydrogeophysical karst	Abu Rajab, Jaf	Jordan	NEAR SURFACE GEOPHYSICS	0
Geophysics	Automated resistivity	Pan, Yuying; J	China	ENVIRONMENTAL SCIENCE AND PO	0
Geophysics	GPR & 2D resistivity	Shaaban, Fath	Saudi Arabia	ARABIAN JOURNAL OF GEOSCIENC	0
Geophysics	LNAPL detection via amplitude domain reflectrometry	Francisca, F. M	Argentina	GEOTECHNICAL AND GEOPHYSICA	0
Geophysics	Monitoring biophysicochemical changes - silty soils	Martinho, E.; A	Portugal	GEODERMA	0
Geophysics	GPR vel. Anomolies monitoring of LNAPL	Bradford, John	USA	NEAR-SURFACE GEOPHYSICS AND	0
Geophysics	GPR detection and sample anal	Lu, Qi; Feng, X	China	NEAR-SURFACE GEOPHYSICS AND	0

Most cited post 2010 paper:

Geophysical signatures of microbial activity at hydrocarbon contaminated sites: A review

Atekwana, E.A. & Atekwana, E.A. Surv Geophys (2010) 31: 247.
https://doi.org/10.1007/s10712-009-9089-8

Abstract:
Please see abstract at the above link

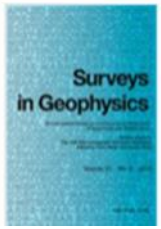


Atekwana & Atekwana (2010)

key points from abstract

- Microorganisms participate in a variety of geologic processes that alter the chemical and physical properties of their environment
- Understanding the geophysical signatures of microbial activity in the environment has formed a new sub-discipline in geophysics called “biogeophysics”
- Biogeophysical signatures of LNAPL sites provide ideal laboratories for investigating microbial-geophysical relationships
- They examine the geophysical responses at contaminated sites over
  - short time frames of weeks to several years when the alteration of the LNAPL by microbial activity has not occurred to a significant extent,
  - and over the long-term of several years to decades, when significant microbial degradation of the LNAPL has occurred

… …



Atekwana & Atekwana (2010)

key points from abstract

- Microbial processes profoundly alter the contam. environment causing marked changes in the petrophysical properties, mineralogy, solute concentration of pore fluids, and temperature.
- A variety of techniques (electrical resistivity, induced polarization, electromagnetic induction, ground penetrating radar, and self potential) may define the contam. zones because of the new physical properties imparted by microbial processes.
- Changes in physical properties of the contaminated environment vary spatially as microbial processes are controlled by the spatial distribution of the contaminant.
- Geophysical studies must consider spatial variations in the physical properties during survey design, data analysis, and interpretation.
- **Geophysical data interpretation from surveys conducted at LNAPL-contaminated sites without a microbial and geochemical context may lead to ambiguous conclusions.**

2nd most cited post-2010 paper:

Orozco et al. (2012)

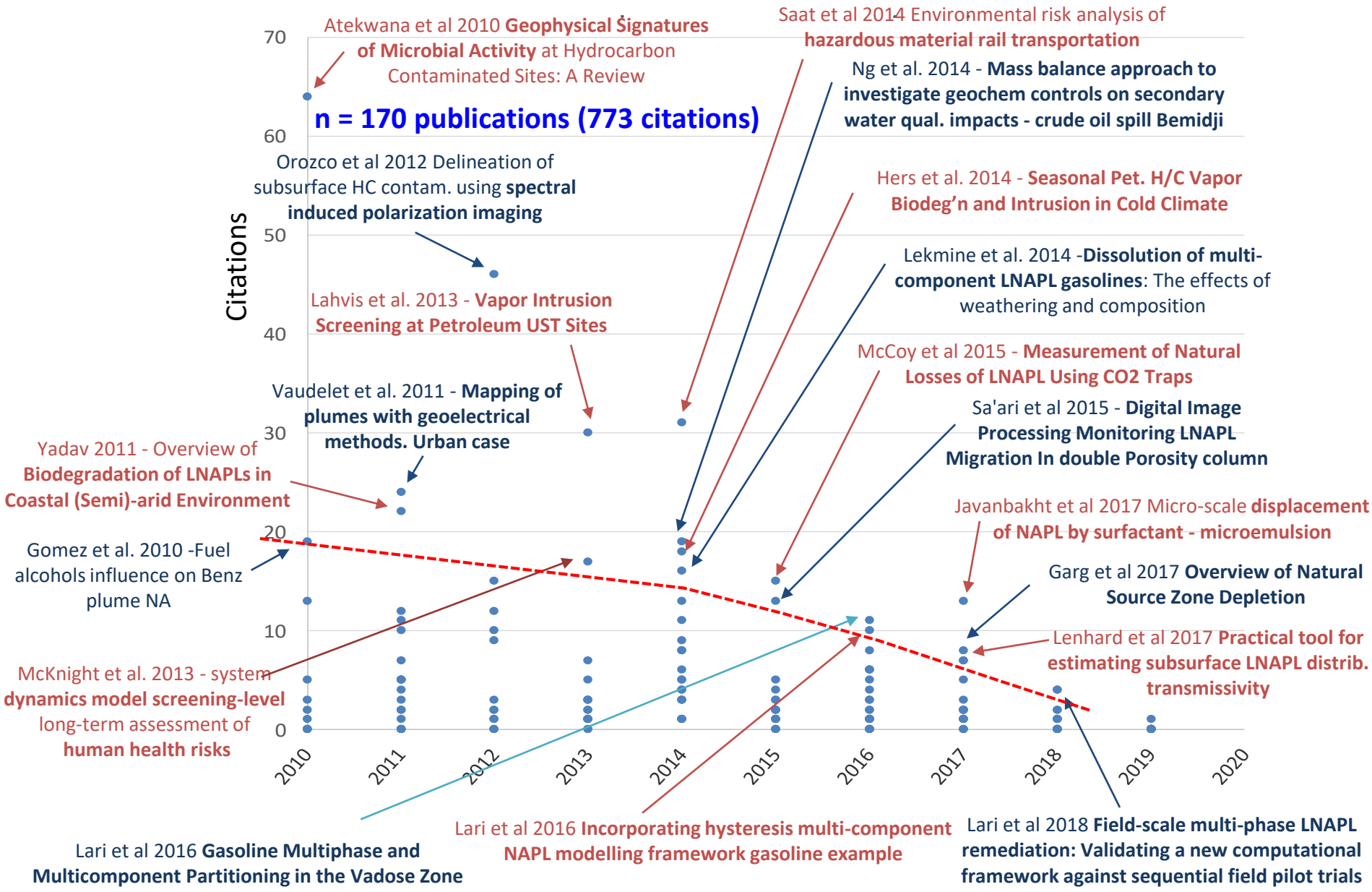
Delineation of subsurface hydrocarbon contamination at a former hydrogenation plant using spectral induced polarization imaging

Journal of Contaminant Hydrology 136-137, (2012) 131 – 144

Please see abstract at:

https://doi.org/10.1016/j.jconhyd.2012.06.001

‘Cream-rises-to-the-top publications’ (2010-19)



A practical tool for estimating subsurface LNAPL distributions and transmissivity using current and historical fluid levels in groundwater wells: Effects of entrapped and residual LNAPL

Lenhard, R.J., Rayner, J.L. and Davis, G.B., 2017. A practical tool for estimating subsurface LNAPL distributions and transmissivity using current and historical fluid levels in groundwater wells: Effects of entrapped and residual LNAPL. *Journal of contaminant hydrology*, *205*, pp.1-11.

Please see abstract at: https://doi.org/10.1016/j.jconhyd.2017.06.002

Natural Source Zone Depletion (NSZD)
incl. Natural Attenuation (NA)

- 26 LNAPL publications related to NSZD
- Subject of recent CL:AIRE bulletin from which a few slides are included:
  - CL:AIRE (2019) - Rivett, M.O., Sweeney, R., 2019. An introduction to natural source zone depletion at LNAPL sites. CL:AIRE Technical Bulletin TB20. https://www.claire.co.uk/component/phocadownload/category/17-technical-bulletins?download=681:tb-20-an-introduction-to-natural-source-zone-depletion-at-lnapl-sites

CL:AIRE (2019)

Natural source-zone depletion NSZD

- NSZD describes the naturally occurring processes that collectively result in the depletion of chemical contaminant mass from a (LNAPL) source zone.
- Over time, source zone depletion typically results in decreased receptor risks and eventual source exhaustion.
- NSZD processes:
  - **Dissolution** and **vapourisation** physically deplete the LNAPL by mass transfer of chemical constituents to the aqueous (groundwater) and gaseous (soil gas) phases.
  - Degradation of NAPL may also occur due to chemical reaction or **biodegradation**, notably of hydrocarbons (with methanogenesis more significant than previously assumed)

NSZD publications slide 1 of 2

North American study

NSZD (abreviated publication title)	Authors	Author - country 1	Source Title	Citations
Review - geophysical signatures of microbial activity at HC sites	Atekwana, Estella	USA	SURVEYS IN GEOPHYSICS	64
Biodeg of LNAPLs in coastal semi-arid settings	Yadav, Brijesh Ku	India	WATER AIR AND SOIL POLLUTION	22
Geochemical controls on secondary water quality impacts - Bimidji	Ng, G. -H. Crystal	USA	JOURNAL OF CONTAMINANT HYDROLOGY	19
Fuel alcohols influence on Benz plume NA	Gomez, Diego E.;	USA	JOURNAL OF CONTAMINANT HYDROLOGY	19
Seasonal factors Vapour biodegn and VI in cold climates	Hers, Ian; Jourabc	Canada	GROUND WATER MONITORING AND REMEDIAT	18
Multicom LNAPL dissolution - weathering - composition effects	Lekmine, Greg; B	Australia	JOURNAL OF CONTAMINANT HYDROLOGY	16
Natural losses of LNAPL measured via CO2 traps	McCoy, Kevin; Zir	USA	GROUNDWATER	15
Volatile HC loss from LNAPL oil	Baedecker, Mary	USA	JOURNAL OF CONTAMINANT HYDROLOGY	12
NSZD overview	**Garg, Sanjay; Ne**	**USA**	**GROUND WATER MONITORING AND REMEDIA**	**8**
Temp influence on anaerobic biotransformation - microbial coummunity in LNAPL	Zeman, Natalie R.	USA	BIODEGRADATION	8
compositional heterogeneity dissolution non-ideal LNAPL mixtures	Vasudevan, M.; Jo	India	JOURNAL OF CONTAMINANT HYDROLOGY	6
Baterial communities in LNAPL body	Irianni-Renno, Ma	USA	APPLIED MICROBIOLOGY AND BIOTECHNOLOG	4
Source zone attenuation at sites with mobile LNAPL	Kulkarni, Poonam	USA	SOIL & SEDIMENT CONTAMINATION	3

NSZD slide 2 of 2

North American study

NSZD (abreviated publication title)	Authors	Author - country 1	Source Title	Citations
Geohpysical, geochem - microbiol integarted characterisation aged source	Arato, Alessandro	Italy	ENVIRONMENTAL SCIENCE AND POLLUTION R	3
Constant / transient Source zone plume evolution	Thornton, Steven	UK	GROUND WATER MONITORING AND REMEDIAT	3
Bubble VOC transport from smear zones	Soucy, Nicole C.;	Canada	ENVIRONMENTAL SCIENCE & TECHNOLOGY	1
Respiration emissions petroleum spill sites	McAlexander, Ber	USA	REMEDIATION-THE JOURNAL OF ENVIRONMEN	1
Oxygen transport - capillary fringe in LNAPL pool	Ha, Jeong-Hyub;	Korea	JOURNAL OF ENVIRONMENTAL ENGINEERING	1
Precip influence on LNAPL recovery - lab & field	Wang, W.; Kuo, T	Taiwan	JOURNAL OF PETROLEUM SCIENCE AND ENGI	1
Cylic freeze-thaw influence on LNAPL mobilisation - dissolution	Iwakun, Olumide;	Canada	COLD REGIONS SCIENCE AND TECHNOLOGY	1
Review NSZD and modelling approaches	Lari, Kaveh Sookh	Australia	WATER RESEARCH	0
NSZD - semi-arid site	McAlexander, Ber	USA	GROUND WATER MONITORING AND REMEDIAT	0
Single well tracer dilution to evaluate LNAPL flux	Lago, Gabriel Paiv	Australia	GROUNDWATER	0
Single well tracer dilution to evaluate LNAPL flux	Sale, Tom; Mahle	USA	GROUNDWATER	0
Monitoring biophysicochemical changes - silty soils	Martinho, E.; Abre	Portugal	GEODERMA	0
Chlorinated ethene plume mign at LNAPL pet. Site	McBean, Edward	Canada	CALIBRATION AND RELIABILITY IN GROUNDW	0

NSZD
Ng et al. (2014) and others…

See abstract at:

https://doi.org/10.1016/j.jconhyd.2014.04.006

• Meckenstock, R.U., F. von Netzer, C. Stumpp, T. Lueders, A.M. Himmelberg, N. Hertkorn, P. Schmitt-Kopplin, M. Harir, R. Hosein, S. Haque, and D. Schulze-Makuch. 2014. **Water droplets in oil are microhabitats for microbial life.** Science 345:673-676.

• Molins, S., Mayer, K.U., Amos, R.T., Bekins, B.A. 2010, **Vadose zone attenuation of organic compounds at a crude oil spill site-interactions between biogeochemical reactions and multicomponent gas transport.** Journal of Contaminant Hydrology, 112: 15–29.

• **Ng, G.-H.C., B.A. Bekins, I.M. Cozzarelli, M.J. Baedecker, P.C. Bennett, and R.T. Amos. 2014. A mass balance approach to investigating geochemical controls on secondary water quality impacts at a crude oil spill site near Bemidji, MN. Journal of Contaminant Hydrology 164:1-15.**

• Ng, G.-H.C., B.A. Bekins, I.M. Cozzarelli, M.J. Baedecker, P.C. Bennett, R.T. Amos, and W.N. Herkelrath. 2015. **Reactive transport modeling of geochemical controls on secondary water quality impacts at a crude oil spill site near Bemidji, MN.** Water Resources Research 51:4156-4183.

NSZD - Ng et al. (2014)

Secondary water quality impacts can result from a broad range of coupled reactions triggered by primary groundwater contaminants. Data from a crude-oil spill research site near Bemidji, MN provide an ideal test case for investigating the complex interactions controlling secondary impacts, including depleted dissolved oxygen and elevated organic carbon, inorganic carbon, CH_4, Mn, Fe, and other dissolved ions. To better understand these secondary impacts, this study began with an extensive data compilation of various data types, comprising aqueous, sediment, gas, and oil phases, covering a 260 m cross-sectional domain over 30 years. Mass balance calculations are used to quantify pathways that control secondary components, by using the data to constrain the sources and sinks for the important redox processes. The results show that oil constituents other than BTEX (benzene, toluene, ethylbenzene, *o*-, *m*- and *p*-xylenes), including *n*-alkanes and other aromatic compounds, play significant roles in plume evolution and secondary water quality impacts. The analysis underscores previous results on the importance of non-aqueous phases. Over 99.9% of the Fe^{2+} plume is attenuated by immobilization on sediments as Fe(II) and 85–95% of the carbon biodegradation products are outgassed. Gaps identified in carbon and Fe mass balances and in pH buffering mechanisms are used to formulate a new conceptual model. This new model includes direct out-gassing of CH_4 and CO_2 from organic carbon biodegradation, dissolution of directly produced CO_2, and sorption with H^+ exchange to improve pH buffering. The identification of these mechanisms extends understanding of natural attenuation of potential secondary impacts at enhanced reductive dechlorination sites, particularly for reduced Fe plumes, produced CH_4, and pH perturbations.

NSZD - Garg et al. (2017)

Garg, S., Newell, C.J., Kulkarni, P.R., King, D.C., Adamson, D.T., Renno, M.I., and T. Sale. 2017.

Overview of natural source zone depletion: Processes, controlling factors, and composition change.

Groundwater Monitoring & Remediation, 37: 62-81.

See abstract at and Figure 1 in particular:

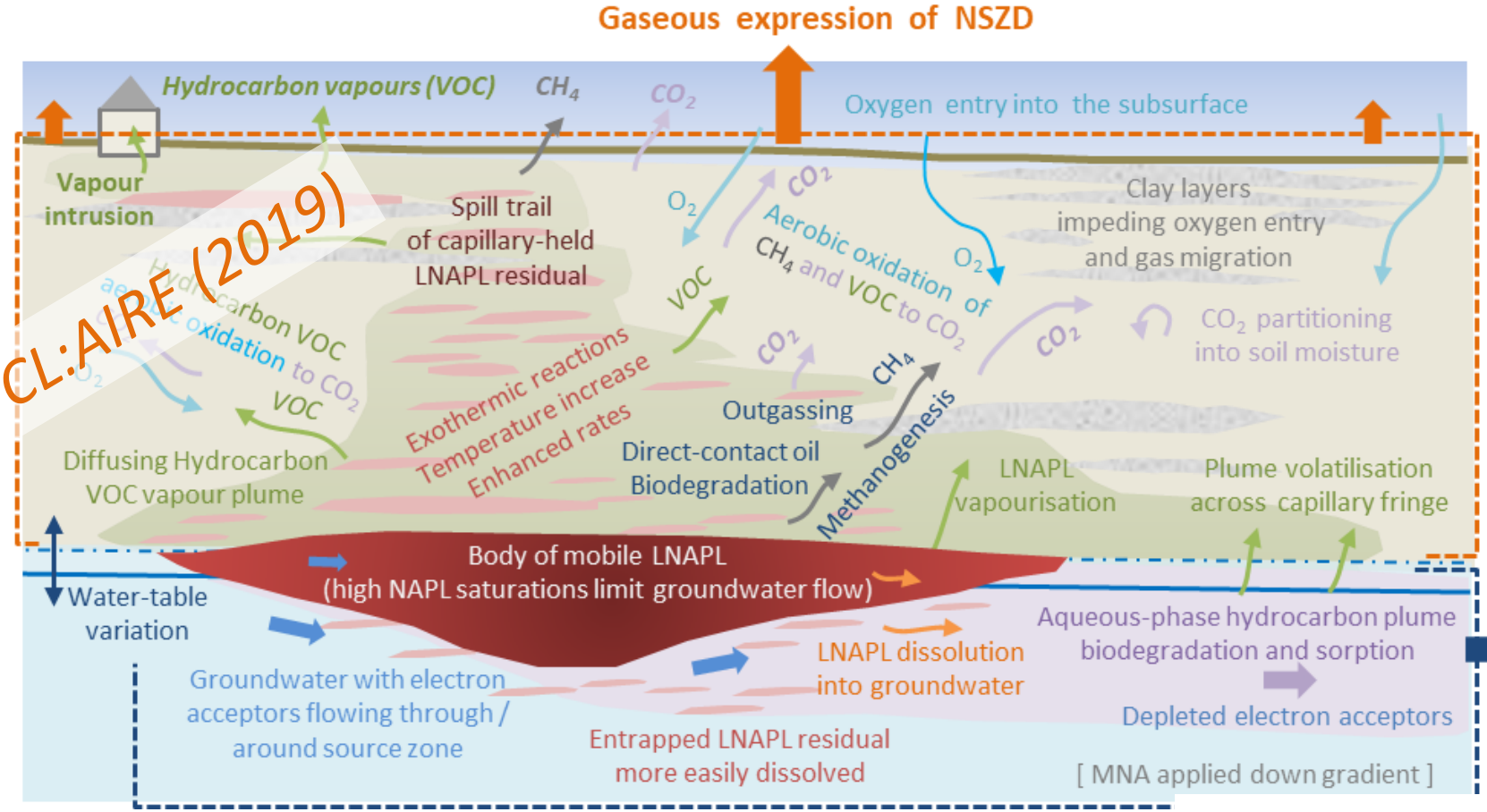
https://doi.org/10.1111/gwmr.12219

Recent guidance documents from US and Aus.

- Several guidance documents on LNAPL site assessment of NSZD occurrence and its potential significance to remediation recently published:
  - **API (2017)** *Quantification of Vapor Phase-Related NSZD Processes*
  - **ITRC (2018)** *LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies*. LNAPL-3 (Updating ITRC (2009))
  - **CRC CARE (2018)** *Technical measurement guidance for LNAPL natural source zone depletion*

Processes controlling NSZD expression

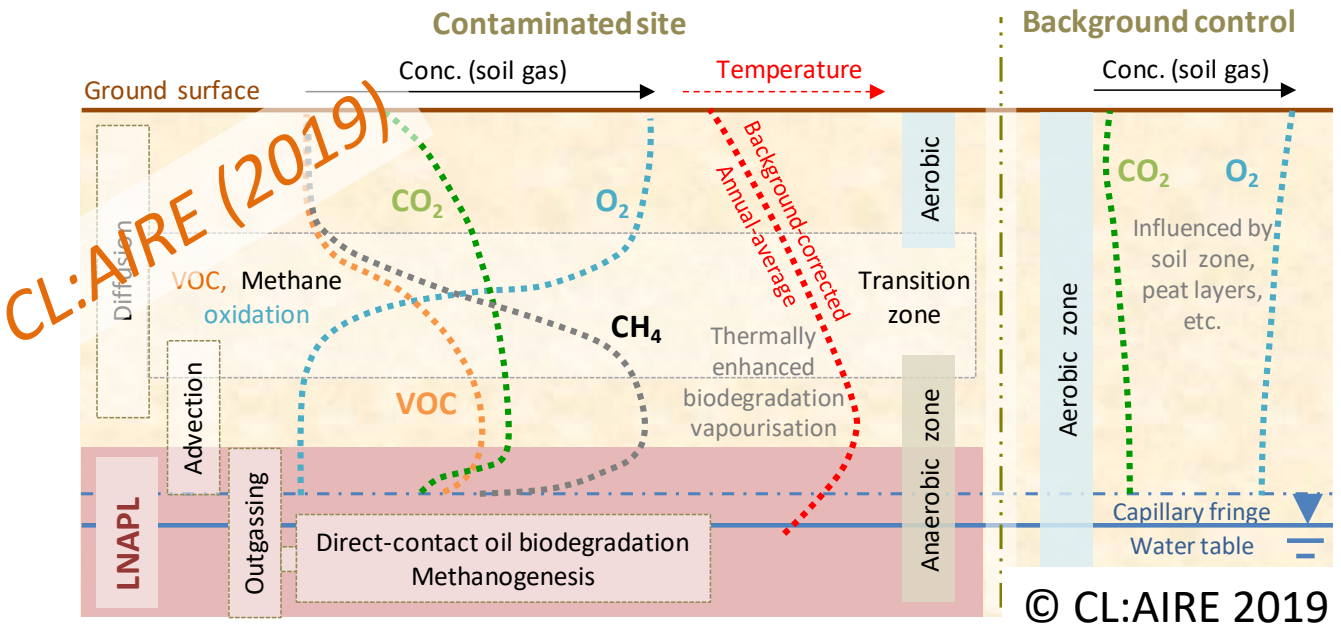
- Overall expression of NSZD may segregate the contributions to source depletion to:



https://www.claire.co.uk/component/phocadownload/category/17-technical-bulletins?download=681:tb-20-an-introduction-to-natural-source-zone-depletion-at-lnapl-sites

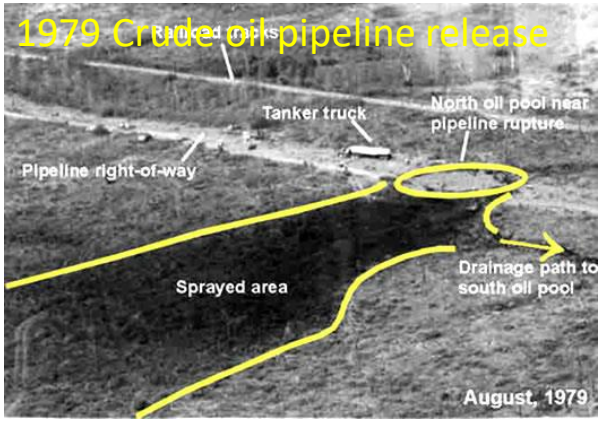
Diffusion with biodegradation attenuation

https://www.claire.co.uk/component/phocadownload/category/17-technical-bulletins?download=681:tb-20-an-introduction-to-natural-source-zone-depletion-at-lnapl-sites



- Diffusion control as air-phase diffusion coeff. for VOCs are ~ four orders of magnitude greater than aqueous-phase diff'n coeff.
- Steep conc. gradients towards surface drive diffusive fluxes
- But, O_2 from surface allows shallow aerobic biodegradation of VOCs and CH_4 to CO_2 gas, thereby attenuating breakthroughs
- Quasi steady-state profiles of O_2, CO_2, CH_4 and VOC develop
- Gaseous expression of NSZD estimated from these profiles

Direct biodegradation of LNAPL - Methanogenesis



https://toxics.usgs.gov/photo_gallery/**bemidji**_all.html

- **Direct biodegradation of LNAPL** (direct-contact oil biodegradation) - **methanogenesis** are becoming recognised as important NSZD processes countering the belief that biodegradation of source zone mass is limited by dissolution from the LNAPL to the aqueous phase
- Evidences (Meckenstock et al., 2014; Hua & Wang, 2014; Ng et al., 2014, 2015):
  - **Bemidji crude oil spill site** evidence of ***direct outgassing of CH_4 and CO_2*** *involving, notably, low solubility compounds (e.g., alkanes) that biodegraded within the LNAPL body;*
  - *Modelling suggested 70% of carbon loss from the oil could be attributed to direct outgassing;*
  - High rates of biodegradation in a bulk oil body containing only minuscule water droplets; and
  - Low solubility NAPL hydrocarbons pseudo-solubilised by biosurfactants, and microorganisms that grow in fatty acids (i.e. not the aqueous phase).

Gaseous expression of NSZD Rate Measurement methods:

- Using **soil gas flux data**:
  - Gradient [Subsurface **depth profile** flux]
  - Passive flux trap [Efflux at **ground surface**]
  - Dynamic closed chamber (DCC) [Efflux at **ground surface**]
- Using **temperature data**:
  - Biogenic heat method [Subsurface **depth profile** flux]
- Using **LNAPL compositional change data:**
  - LNAPL compositional change method [**LNAPL samples** – wells, cores]
  - {method would also include aqueous contribution}

Measurement locations relating to LNAPL Conceptual Site Models

- We need to carefully consider the LNAPL CSM as measurement locations will measure different fluxes and hence NSZD rates

Marine clays

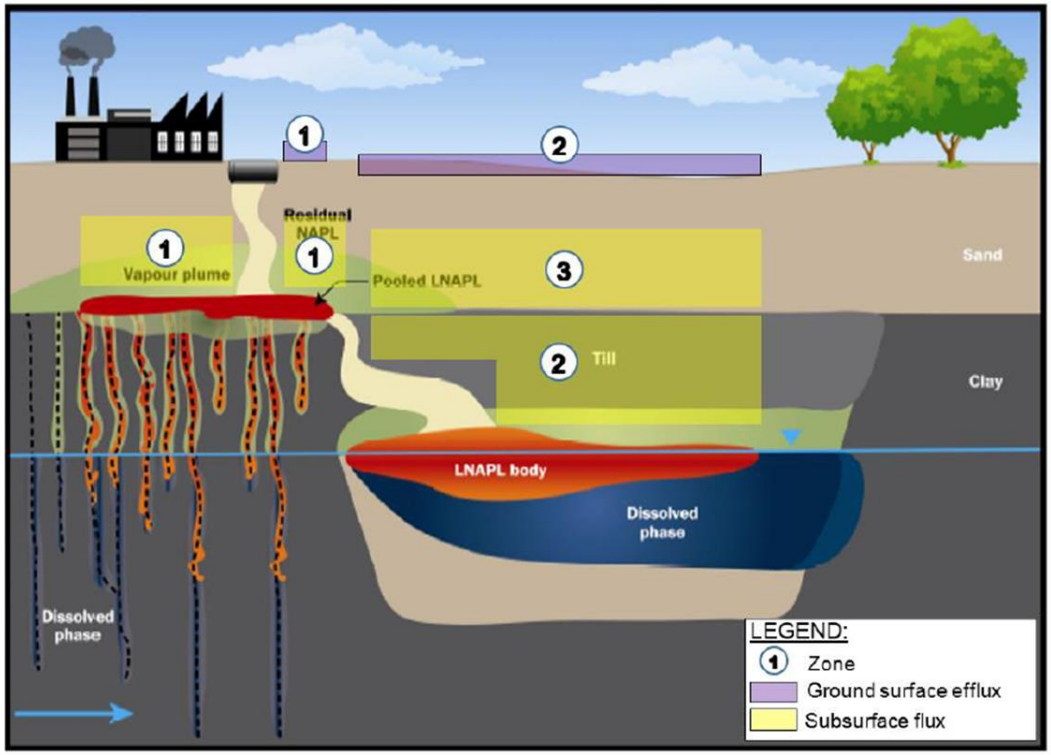


Figure: CRC CARE (2018) (with LNAPL CSM from CL:AIRE (2014) – 'LNAPL Handbook'

Rates via soil gas flux data

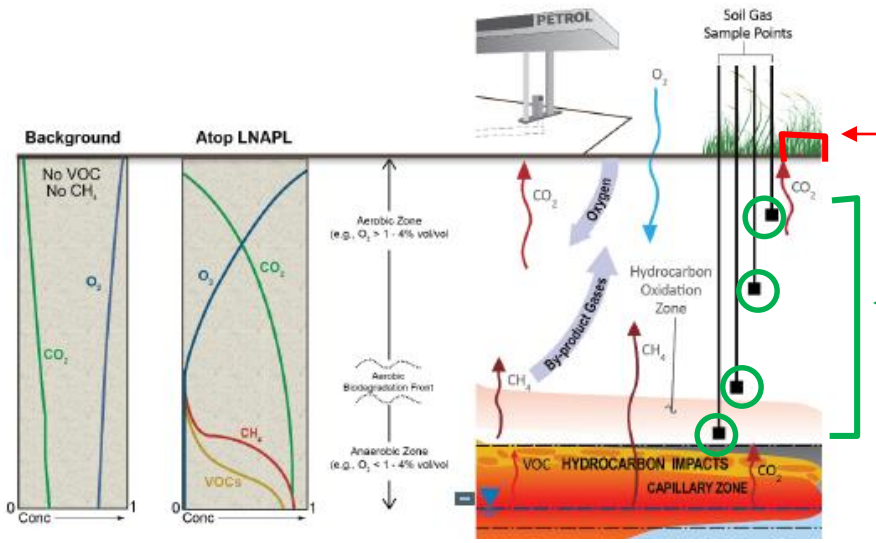


Figure: CRC CARE (2018)

Efflux 'CO_2 traps' or monitoring at surface:

- Passive flux trap
- Dynamic closed chamber (DCC)

- **Gradient** (then $J = D_{eff}\, dC/dz$, Fick's 1st law)

Methanogenesis: $C_8H_{18} + 3.5\ H_2O \rightarrow 1.75\ CO_2\ (g) + 6.25\ CH_4\ (g)$

Methane oxidation: $CH_4 + 2\ O_2 \rightarrow CO_2\ (g) + 2\ H_2O$

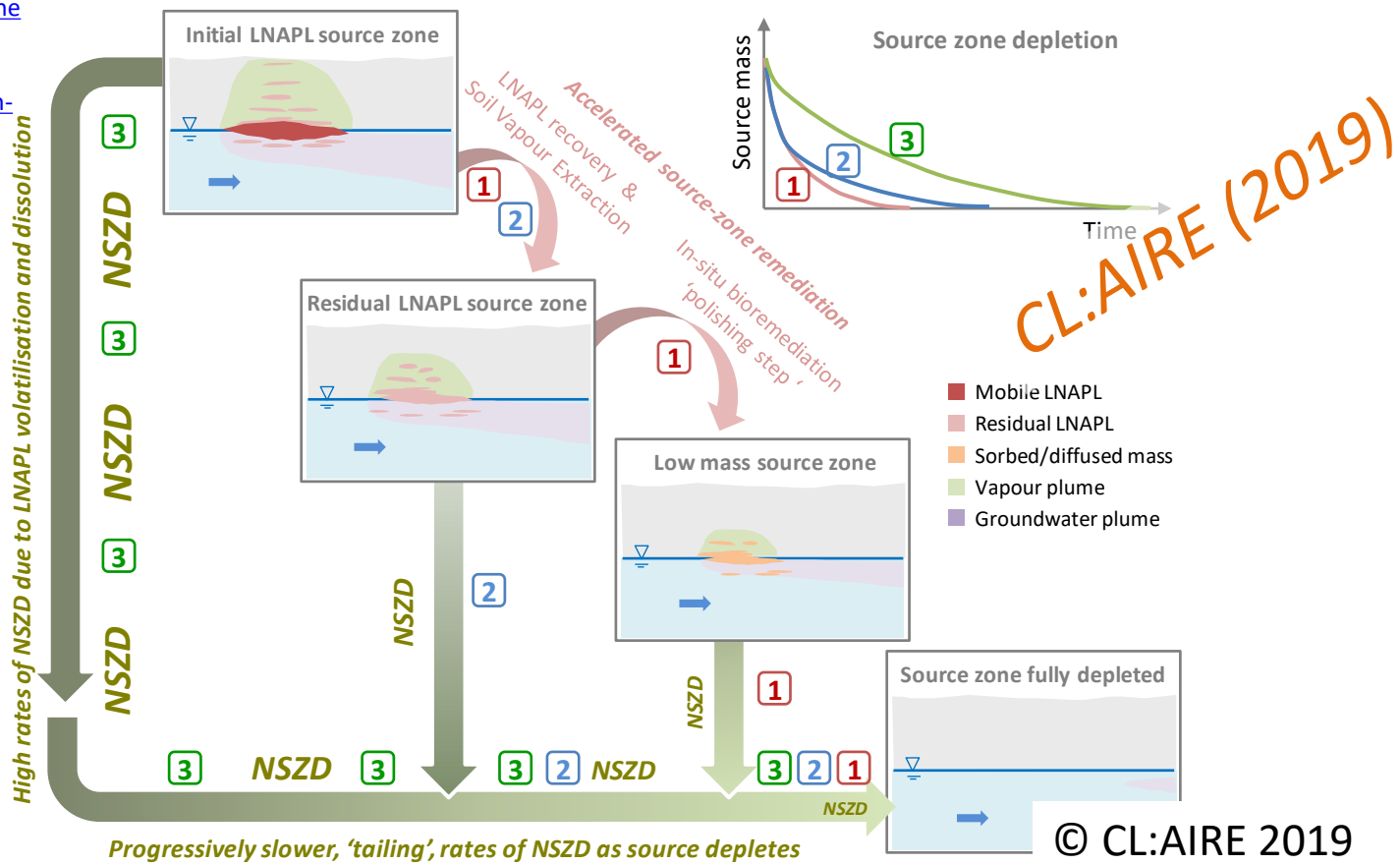
Combined $C_8H_{18} + 12.5\ O_2 \rightarrow 8\ CO_2\ (g) + 9\ H_2O$

- Microbial reactions used for stoichiometric calc. of NSZD [pick most apt HC]
- Locate where use Combined Equn just measuring CO_2,or O_2 [location, CSM]
- Need background due to confounding natural CO_2 production by plants / peat layers etc. [could differentiate by ^{14}C as low in hydrocarbons]
- Assume diffusion dominant (and not advection) [Nitrogen profiles]
- Env. conditions, recharge: D_{eff} sensitivity to water content demands temporal monitoring and a range of D_{eff} values [He, SF_6 tracer tests]
- Heterogeneity may greatly influence profiles, fluxes [do multiple locations]
- Efflux methods [avoid impervious cover, data near rainfall, correct for wind]

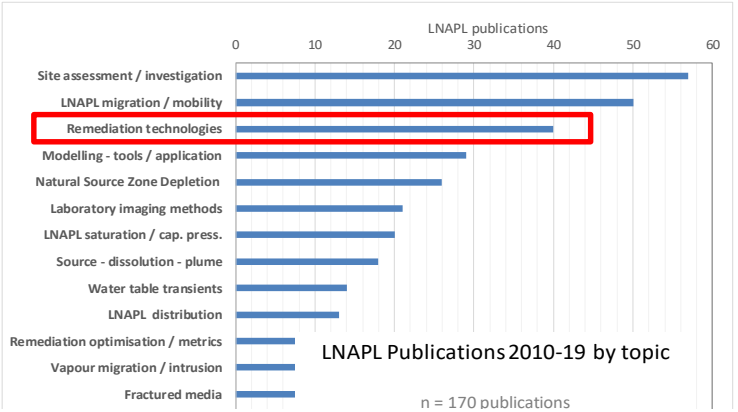
NSZD *versus* more active remediation?

- As with MNA, NSZD is not a trivial undertaking, with issues still to consider for regulatory implementation
- Also, NSZD applicability in UK hydrogeological settings?

https://www.claire.co.uk/component/phocadownload/category/17-technical-bulletins?download=681:tb-20-an-introduction-to-natural-source-zone-depletion-at-lnapl-sites



Remediation Technologies



- 40 of 2010-19 LNAPL publications

Remediation Technology	Publications
	11
	10
	10
Steam injection	1
Thermal	1
Electrocoagulation	1
ISCO	1
Nano—remediation	1
SVE	1
Framework / management	3

Remediation technologies

- Surfactant

Remediation type	Publication	Authors	Author - country 1	Source Title	Publication Year	Total Citations
Surfactant	Micro-scale displacement of NAPL by surfactant and microemulsion in heterogeneous porous media	Javanbakht, Gina; Ars	USA	ADVANCES IN WATER RESOURCES	2017	13
Surfactant	2D sandbox experiments of surfactant foams for mobility control and enhanced LNAPL recovery in layered soils	Longpre-Girard, Mela	Canada	JOURNAL OF CONTAMINANT HYDROLOGY	2016	6
Surfactant	Transparent Aquabeads to Model LNAPL Ganglia Migration Through Surfactant Flushing	Tabe, Kazunori	Japan	GEOTECHNICAL TESTING JOURNAL	2015	5
Surfactant	Centrifuge Modeling of In situ Surfactant Enhanced Flushing of Diesel Contaminated Soil	Pasha, Amin Yousefi	Iran	GEOTECHNICAL TESTING JOURNAL	2011	5
Surfactant	Jet A fuel recovery using micellar flooding: Design and implementation	Kostarelos, Konstant	USA	SCIENCE OF THE TOTAL ENVIRONMENT	2016	2
Surfactant	Impact of heterogeneous properties of soil and LNAPL on surfactant-enhanced capillary desaturation	Robert, Thomas; Mar	Canada	JOURNAL OF CONTAMINANT HYDROLOGY	2017	1
Surfactant	Field Tracer Test for the Design of LNAPL Source Zone Surfactant Flushing	Robert, Thomas; Mar	Canada	GROUND WATER MONITORING AND REMEDIATION	2016	1
Surfactant	Comparative study of the impacts of soil wettability during entrapped LNAPL removal by surfactant flooding in two different sand media	Jacome, Luz A. Puer	Canada	JOURNAL OF SOILS AND SEDIMENTS	2015	1
Surfactant	An initial study on soil wettability effects during entrapped LNAPL removal by surfactant flooding in coarse-grained sand media	Jacome, Luz A. Puer	Canada	JOURNAL OF SOILS AND SEDIMENTS	2013	1
Surfactant	LNAPL Removal from Unsaturated Porous Media Using Surfactant Infiltration	Zhong, Lirong; Oostro	USA	VADOSE ZONE JOURNAL	2012	1
Surfactant	LNAPL fate and removal from vadose zone in surfactant infiltration: Column experiment investigation	Zhong, Lirong; Oostro	USA	ABSTRACTS OF PAPERS OF THE AMERICAN CHEMICAL SOCIETY	2011	0

Remediation technologies

LNAPL Recovery

Remediation type	Publication	Authors	Author - country 1	Source Title	Publication Year	Total Citations
LNAPL recovery	Quasi-Monte Carlo based global uncertainty and sensitivity analysis in modeling free product migration and recovery from petroleum-contaminated aquifers	He, Li; Huang, Gordo	China	JOURNAL OF HAZARDOUS MATERIALS	2012	12
LNAPL recovery	Free-product plume distribution and recovery modeling prediction in a diesel-contaminated volcanic aquifer	Hernandez-Espriu, A	Mexico	PHYSICS AND CHEMISTRY OF THE EARTH	2012	10
LNAPL recovery	Multi-objective optimization for free-phase LNAPL recovery using evolutionary computation algorithms	Dokou, Zoi; Karatzas	Greece	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	2013	7
LNAPL recovery	Rn-222 as Natural Tracer for LNAPL Recovery in a Crude Oil-Contaminated Aquifer	Ponsin, Violaine; Cha	France	GROUND WATER MONITORING AND REMEDIATION	2015	2
LNAPL recovery	Effect of precipitation on LNAPL recovery performance: An integration of laboratory and field results	Wang, W.; Kuo, T.; C	Taiwan	JOURNAL OF PETROLEUM SCIENCE AND ENGINEERING	2014	1
LNAPL recovery	Pore-scale removal mechanisms of residual light non-aqueous phase liquids in porous media	Li, Helian; Chen, Jiaju	China	ENVIRONMENTAL EARTH SCIENCES	2011	1
LNAPL recovery	An Approach for Passive Removal of Residual LNAPL from Groundwater	Svitana, Kevin; South	USA	GROUND WATER MONITORING AND REMEDIATION	2019	0
LNAPL recovery	Methodological approach for the estimation of recoverable LNAPL volumes in aquifer and for the analysis of residual phase behaviour in laboratory	Frollini, Eleonora	Italy	ACQUE SOTTERRANEE-ITALIAN JOURNAL OF GROUNDWATER	2017	0
LNAPL recovery	Optimized prefabricated vertical wells for light nonaqueous phase liquid recovery	Sharmin, N.; Gabr, M	Bangladesh	CANADIAN GEOTECHNICAL JOURNAL	2012	0
LNAPL recovery	Employing evolutionary algorithms for optimizing free-phase LNAPL recovery	Dokou, Zoi; Karatzas	Greece	PROCEEDINGS OF THE XVIII INTERNATIONAL CONFERENCE ON COMPUTATIONAL METHODS IN WATER RESOURCES (CMWR 2010)	2010	0

Remediation technologies

Bioremediation

Remediation type	Publication	Authors	Author - country 1	Source Title	Publication Year	Total Citations
Bioremediation	An Overview of Biodegradation of LNAPLs in Coastal (Semi)-arid Environment	Yadav, Brijesh Kuma	India	WATER AIR AND SOIL POLLUTION	2011	22
Bioremediation	Temperature impacts on anaerobic biotransformation of LNAPL and concurrent shifts in microbial community structure	Zeman, Natalie R.; R	USA	BIODEGRADATION	2014	8
Bioremediation	Comparison of bacterial and archaeal communities in depth-resolved zones in an LNAPL body	Irianni-Renno, Maria;	USA	APPLIED MICROBIOLOGY AND BIOTECHNOLOGY	2016	4
Bioremediation	Remediation of LNAPL Contaminated Groundwater Using Plant-Assisted Biostimulation and Bioaugmentation Methods	Yadav, Brijesh K.; Ar	India	WATER AIR AND SOIL POLLUTION	2014	4
Bioremediation	Remediation in Situ of Hydrocarbons by Combined Treatment in a Contaminated Alluvial Soil due to an Accidental Spill of LNAPL	Trulli, Ettore; Morosir	Italy	SUSTAINABILITY	2016	3
Bioremediation	Simulation of Subsurface Multiphase Contaminant Extraction Using a Bioslurping Well Model	de Souza, Michelle M	Brazil	TRANSPORT IN POROUS MEDIA	2016	3
Bioremediation	Hydrocarbon Remediation by Natural Attenuation at Baruwa, Lagos Nigeria	Uduebor, Micheal A.;	Nigeria	ELECTRONIC JOURNAL OF GEOTECHNICAL ENGINEERING	2016	2
Bioremediation	Monitoring In Situ Biodegradation of MTBE Using Multiple Rounds of Compound-Specific Stable Carbon Isotope Analysis	Lu, Jun; Muramoto, F	USA	GROUND WATER MONITORING AND REMEDIATION	2016	0
Bioremediation	Chlorinated ethene plume migration in groundwater at free-phase petroleum sites	McBean, Edward	Canada	CALIBRATION AND RELIABILITY IN GROUNDWATER MODELLING: MANAGING GROUNDWATER AND THE ENVIRONMENT	2011	0
Bioremediation	Biosparging successfully limited fugitive VOCs while remediating residual weathered gasoline in a shallow sand aquifer	Johnston, C. D.; Woo	Australia	GQ10: GROUNDWATER QUALITY MANAGEMENT IN A RAPIDLY CHANGING WORLD	2011	0

Remediation technologies

Misc.

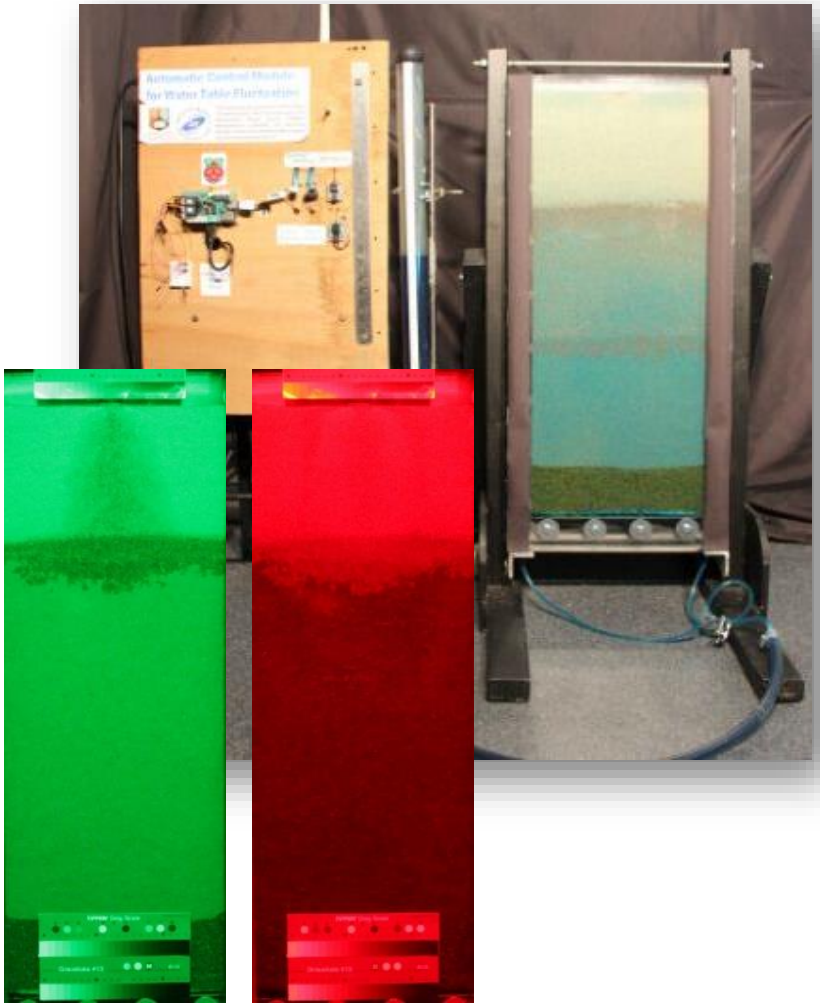
Remediation type	Publication	Authors	Author - country 1	Source Title	Publication Year	Total Citations
Steam injection	Remediation of the unsaturated zone of NAPL-polluted low permeability soils with steam injection: an experimental study	Tzovolou, Dimitra N.;	Greece	JOURNAL OF SOILS AND SEDIMENTS	2011	11
Thermal	Can thermal soil remediation be sustainable? A case study of the environmental merit of the remediation of a site contaminated by a light non-aqueous phase liquid (LNAPL)	Cappuyns, Valerie; B	Belgium	JOURNAL OF INTEGRATIVE ENVIRONMENTAL SCIENCES	2011	3
Electrocoagulation	Experimental study on the transport characteristics of buried pipeline leakage and the performance of groundwater remediation system	Jiang, Wenming; Yar	China	ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH	2018	1
ISCO	A Modified Approach for in Situ Chemical Oxidation Coupled to Biodegradation Enhances Light Nonaqueous Phase Liquid Source Zone Remediation	Fedrizzi, Franciele; F	Brazil	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2017	1
Nano--remediation	Targeted nanoparticle binding & detection in petroleum hydrocarbon impacted porous media	Linley, Stuart; Holme	Canada	CHEMOSPHERE	2019	1
SVE	Mathematical Model for Multiphase Extraction Simulation	Kacem, Mariem; Ben	France	JOURNAL OF ENVIRONMENTAL ENGINEERING	2018	1
Framework - Management	Field-scale multi-phase LNAPL remediation: Validating a new computational framework against sequential field pilot trials	Lari, Kaveh Sookhak;	Australia	JOURNAL OF HAZARDOUS MATERIALS	2018	4
Framework - Management	Contemporary Management of Sites with Petroleum LNAPL Presence	Suthersan, Suthan; K	USA	GROUND WATER MONITORING AND REMEDIATION	2015	4
Framework - Management	Use of chemical fingerprint data to enhance remedial site investigations at petroleum impacted sites	Lu, Jun	USA	ENVIRONMENTAL FORENSICS	2016	1

Laboratory methods

- Digital image analysis – 5 publications
- Some of our unpublished UK work…(at least in journals):
  - Video from Univ. of Birmingham PhD study by: **Sun, Simiao, 2017**. Transient water table influence upon light non-aqueous phase liquid (LNAPL) redistribution: Laboratory and modelling studies. http://etheses.bham.ac.uk/7236/
- Hopefully journal publications that '*do not get away*'

Transient water table influence upon LNAPL redistribution

Simiao Sun, Alan W. Herbert, Michael O. Rivett



Time-lapse multi-spectral photography

Has been developed to real-time image multi-phase flow and quantify saturations of dyed LNAPL and dyed water and, by their difference, air. Experiments involve development of automated, computer-controlled (Paspberry Pi), oscillation of the water table. The study is based upon application of Beer-lambert law that light intensities (Optical density) are proportional to the fluid saturations.

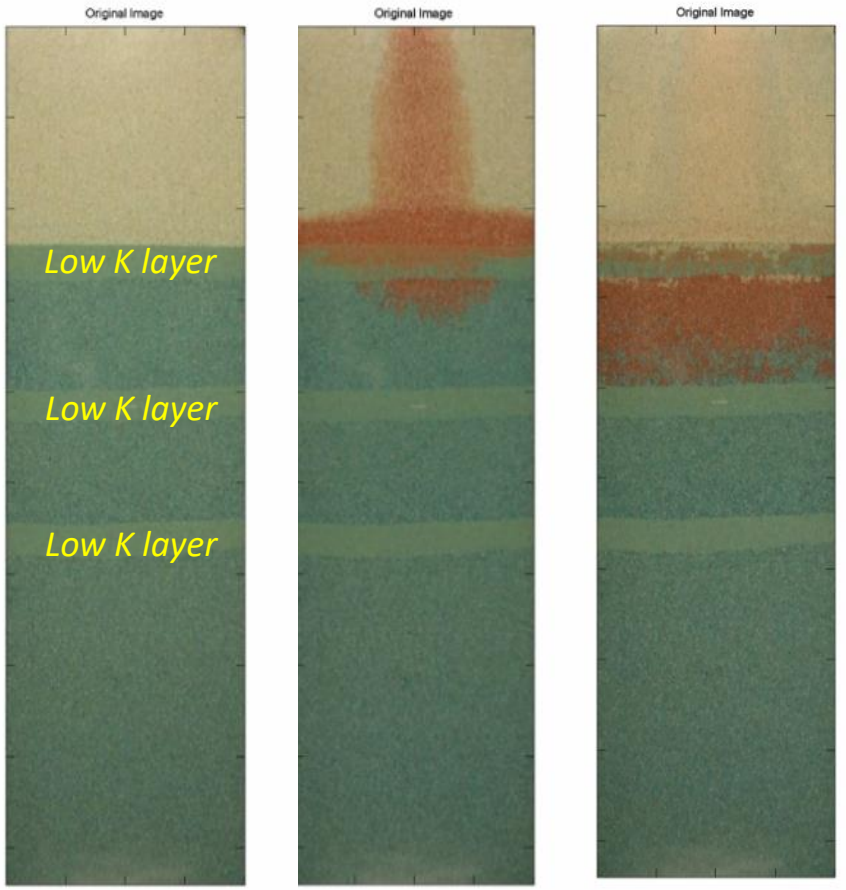
Image analysis (Batch processing)

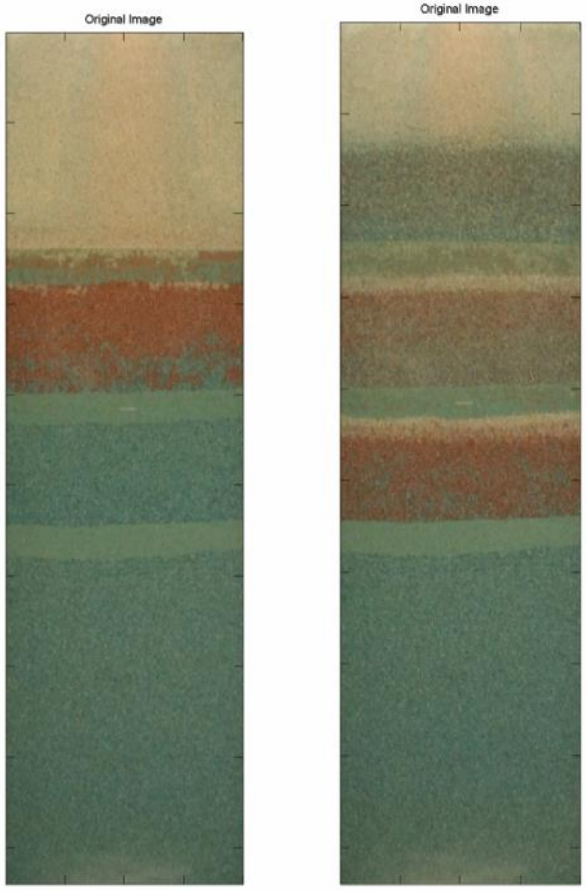
Has been realised with MATLAB using 2 pairs of photos taken under 2 different narrow band-pass filters allowing saturations of NAPL and water to be obtained via the following calibrated relationships:

$$\begin{cases} S_{W2} = \dfrac{\lambda_i^O\left(D_k^{OW} - \beta_k^{OW}\right) - \lambda_k^O\left(D_i^{OW} - \beta_i^{OW}\right)}{\lambda_k^O\lambda_i^W - \lambda_i^O\lambda_k^W} + S_{W1} \\ S_{O2} = \dfrac{\lambda_k^W\left(D_i^{OW} - \beta_i^{OW}\right) - \lambda_i^W\left(D_k^{OW} - \beta_k^{OW}\right)}{\lambda_k^O\lambda_i^W - \lambda_i^O\lambda_k^W} + S_{O1} \end{cases} \quad i,k = 532, 632, 980nm$$

Making life difficult, “Confined LNAPL”

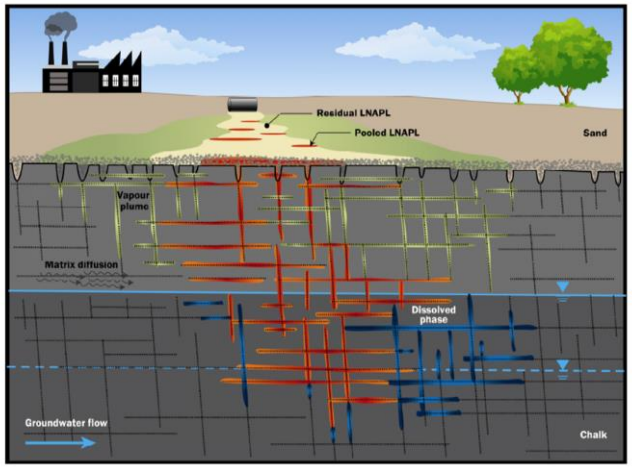
- Initial spill release
- Water table fluctuation





Video stills from Univ. of Birmingham PhD study by: Sun, Simiao, 2017. Transient water table influence upon light non-aqueous phase liquid (LNAPL) redistribution: Laboratory and modelling studies. http://etheses.bham.ac.uk/7236/

A review of the recent international LNAPL literature

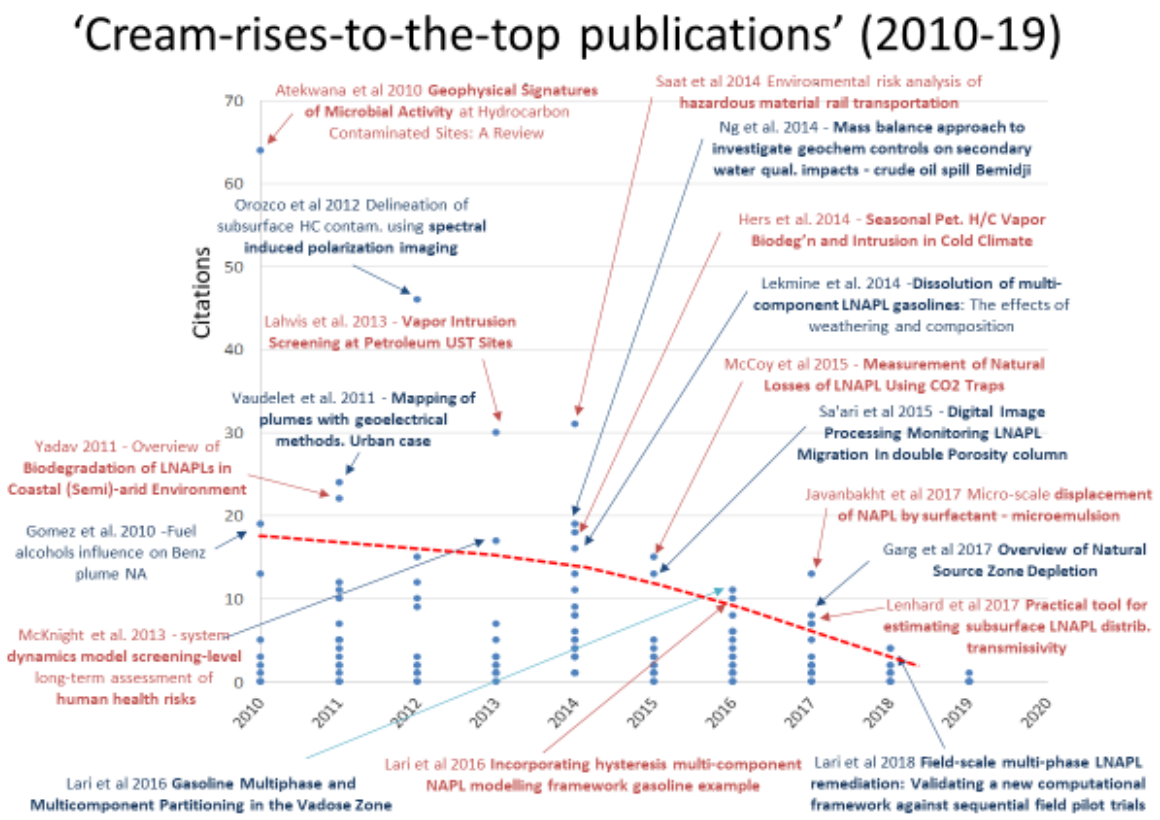


CL:AIRE (2014)

- **are we missing out on something?**
  - More than likely (?)
- **Does it matter?**
  - Probably (?)
- **What are we going to do about it?**
  - … … …

Suggested LNAPL homework …

- Take a read of the 19 '***Cream-rises-to-the-top publications***' (above the red line, and listed with links on the following two slides)



Email: rivett@groundh2oplus.co.uk to obtain listing

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My L/DNAPL publications since 2010

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