Remediation Industry Best-Practice Guidance: An Illustrated Handbook of LNAPL Transport and Fate in the Subsurface

Michael Rivett, Editor - University of Birmingham, Derek Tomlinson - Geosyntec Consultants, Steven Thornton - University of Sheffield, Alan Thomas - ERM, Stephen Leharne - University of Greenwich, Gary Wealthall - Geosyntec Consultants, Sanjay Garg - Shell Global Solutions, Alwyn Hart, Environment Agency, Jonathan Smith - Shell Global Solutions, Rob Sweeney (rob.sweeney@claire.co.uk) - CL:AIRE, Peter Zeeb - Geosyntec Consultants

1. Introduction

The "LNAPL illustrated handbook" presents best-practice guidance on the behaviour of light non-aqueous phase liquids (LNAPLs) in the subsurface. LNAPLs notably include fuels and oils, and are amongst the most commonly encountered organic contaminants in the subsurface environment due to their ubiquitous use, accidental release and, perhaps, poor (historical) disposal. Central to the LNAPL illustrated handbook and the management of risks posed is the development of conceptual models of LNAPL behaviour in common hydrogeological systems.

The LNAPL illustrated handbook provides an accessible overview of LNAPL behaviour in soil and groundwater, including a series of illustrative conceptual models of LNAPL in different hydrogeological environments, to establish:

- better conceptual understanding of LNAPL transport and fate in the subsurface, on which risk-management strategies can be developed;
- more effective site characterisation and robust risk prediction;
- risk-based management of LNAPL releases that is more sustainable;
- improved understanding of where and/or when specific LNAPL remedial techniques are likely to be effective in performance and cost.

2. Types of LNAPL and their properties

LNAPLs are hydrophobic organic liquids that are immiscible with water and are less dense than water. A LNAPL hence exists as a separate organic phase when in contact with water and is able to 'float' upon that aqueous-phase liquid. They are amongst the most frequently encountered organic contaminants in the subsurface environment. They include a wide range of substances, but the most common types are fuels, such as petrol (gasoline), diesel, heating oils and jet fuel (kerosene), and lubricants. LNAPL releases to ground can result from a range of release mechanisms, including accidental leakage from above ground and underground storage tanks and associated pipelines as well as accidental release during handling, storage or transfer at fuel manufacturing facilities, refineries, bulk-product terminals, petrol filling stations, airports, military bases, and from smaller scale storage at domestic properties, industrial facilities and farms.

Section 2 of the LNAPL illustrated handbook provides details of the types and uses of commonly encountered LNAPLs, elaborating on the key physical-chemical properties - such as density, viscosity, interfacial tension (against water), composition, aqueous solubility, vapour pressure and wetting behaviour - that influence their environmental fate.

3. LNAPL transport and distribution

LNAPL subsurface transport is complex, being a multi-phase (LNAPL-water-air) system. Unlike dense non-aqueous phase liquids (DNAPLs) that sink in water, LNAPLs are less dense than water and when released to the subsurface they migrate through partially (water) saturated strata until they reach the water table, which impedes (but not completely prevents) their migration deeper due to both increasing water content and associated buoyancy forces arising from the LNAPL-water fluid density contrast. Lateral spread of LNAPL near the water table is determined principally by the subsurface geology, size of the LNAPL release, as well as physical-chemical properties of the LNAPL.

In addition to the above, Section 3 of the LNAPL illustrated handbook covers LNAPL migration in porous media and fractured rock along with factors influencing LNAPL distribution and redistribution following water table fluctuation.

4. LNAPL mass transfer and plume fate

The physical-chemical properties of individual compounds within a LNAPL mixture control rates of partitioning (mass transfer) from the LNAPL to the gas and aqueous phases. This transfer leads to the development of vapour-phase plumes in the unsaturated (vadose, or more accurately partially saturated) zone above the water table and shallow dissolved-phase plumes in groundwater laterally flowing beneath the water table.

Section 4 of the LNAPL illustrated handbook examines these LNAPL mass transfer processes and the fate and transport of the respective plumes that are produced. This includes the role of natural attenuation in their management and risk mitigation. This section also describes natural source zone depletion (NSZD), which simply recognises that LNAPL source zones may deplete naturally. Key LNAPL depletion processes include: LNAPL dissolution into groundwater and biodegradation in the saturated zone; LNAPL vapourisation, volatilisation and biodegradation in the partially saturated zone, and direct biodegradation of LNAPL.

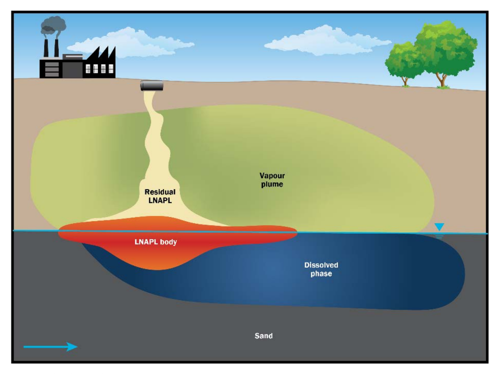
Supported by

5. Conceptual models of LNAPL behaviour

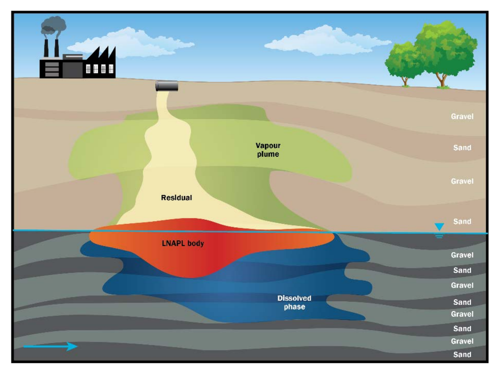
Sections 1-4 of the LNAPL illustrated handbook underpin the development of conceptual models of LNAPL transport and fate across a comprehensive range of common hydrogeological systems. This is considered the handbook hub from which local conceptual site models may be developed that fundamentally support both the characterisation and investigation of sites (*Section 6*) and the management and remediation of sites designed to address unacceptable risks posed (*Section 7*).

The table below summarises the various exemplar hydrogeological environments that could exist based upon commonly encountered aquifer material and flow characteristics. These cover intergranular sediments and bedrocks of contrasting permeability and porosity types, and made (artificial) ground. Section 5 of the LNAPL illustrated handbook further develops these various environments as annotated CSMs (five examples given below). It should be noted, however, that further combinations of the environments are likely (e.g., superficial sediments over fractured bedrock) in which case, it is necessary to understand the LNAPL distribution within the overlying media, and use that as the source to the underlying media.

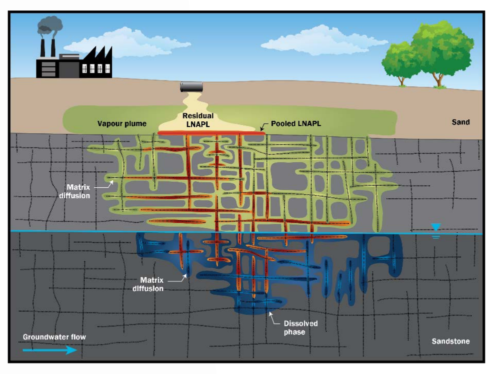
Hydrogeological Environment	Formation characteristics	Flow characteristics	Geological exemplars
Intergranular superficial (drift) sediments	Low heterogeneity	High permeability	Beach Sands
		Low permeability	Marine Clays
	High heterogeneity	High permeability	Glacio-fluvial sands and gravel
		Low permeability	Glacial till
Bedrock	Low matrix porosity	Small aperture fractures	Granite / Igneous rock
		Large aperture fractures	Karst limestone
		Fracture and matrix	Cemented sandstone/gritstone
	High matrix porosity	Large aperture fractures	Chalk
		Small aperture fractures	Shale / Mudstone
		Fracture and matrix	Sandstone
Anthropogenic strata	High heterogeneity	Both Low and High permeability	Made Ground, Backfill



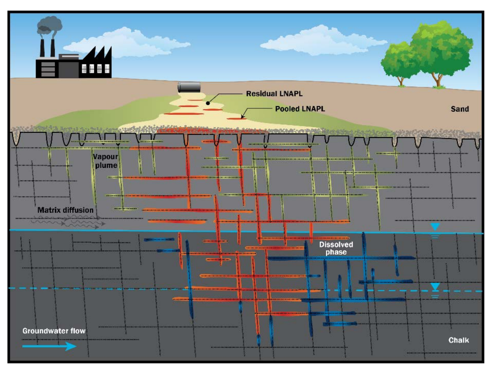
Beach Sands
Low heterogeneity & High permeability



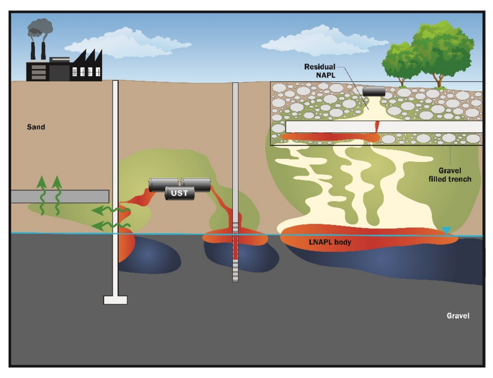
Glacio-fluvial Sands and Gravel
High Heterogeneity & High permeability



Cemented Sandstone / Gritstone
Low matrix porosity & Fracture and matrix flow.



Fractured (Cretaceous) Chalk
High matrix porosity & Large aperture fractures



Made Ground
High heterogeneity & Both high and low permeability

6. Characterising LNAPL sites

Section 6 of the LNAPL illustrated handbook focuses on the characterisation and investigation of LNAPL-impacted sites. Many site investigation methods are listed in the handbook which can be used for porous and fractured media and whilst these methods are not necessary at all sites, the assessment approach needs to be tailored to the site-specific scenario. Further, it should be recognised that site characterisation is not just an initial assessment process, but rather an on-going process that may still be very prominent in the remedial programme for a site.

7. LNAPL management and remediation

Section 7 of the LNAPL illustrated handbook considers how the management and remediation of contaminated soil and groundwater is increasingly undertaken in the context of sustainable risk-based regulatory frameworks. Whilst the details of each regime vary, the requirement for remediation is typically determined following an appraisal of risks that includes an assessment of contaminant sources, pathways and receptors. Where unacceptable risks are confirmed then the development of a remedial strategy evaluates the options to mitigate the risks. This may include treatment of the source, action to break the pathway and/or protection of the receptor. The identification of a suitable remedial technology is then undertaken via a feasibility study or remedial options appraisal that includes a range of criteria including assessment of technical effectiveness, cost, durability, practicality and increasingly, sustainability.

The LNAPL illustrated handbook provides a blend of technical detail and real world conceptualisation of the LNAPL problem and facilitates access to a wealth of detailed research, guidance and case study literature. It will be useful to not only practitioner and research communities, but also to provide an educational resource to others having a less direct interest. The LNAPL illustrated handbook is available for free download from CL:AIRE at: http://www.claire.co.uk/lnapl.