CL:AIRE

guidance bulletin

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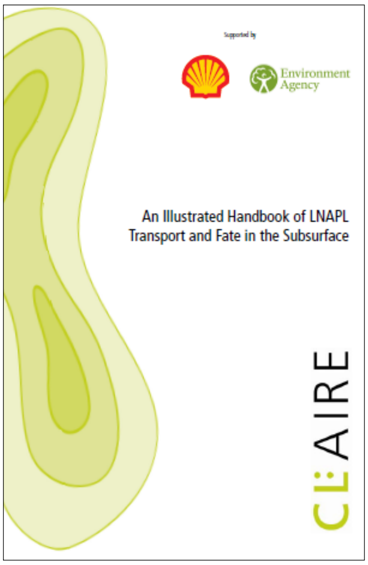
CL:AIRE guidance bulletins describe good practice as it applies to the characterisation, monitoring or remediation of contaminated soil or groundwater. This bulletin summarises "An illustrated handbook of LNAPL transport and fate in the subsurface", published in 2014.

Transport and Fate of LNAPL in the Subsurface

1. Introduction

This bulletin describes an illustrated handbook that 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 will be of benefit to not only practitioner and supporting research communities, but also serve as an educational resource to those having a more peripheral interest (noting a glossary of key technical terms is provided). It contains a mix of technical detail and practical conceptualisation of the problem that is relevant to real world scenarios. It also serves to provide a convenient interface to a wealth of modern and established research, guidance and case study literature.

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.

The most frequently encountered LNAPLs are complex mixtures of organic compounds. Such LNAPLs are compositionally complex containing aliphatic and aromatic hydrocarbons in varying ratios. They may be further formulated with a range of additives that enhance and extend their performance as fuels or lubricants. 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.

Mobility of the LNAPL is influenced by the size of the release and the fluid's viscosity. Low viscosity LNAPL releases (such as petrol) may stabilise within weeks to months, whereas high viscosity LNAPLs (such as heating oil or bitumen) flow more slowly for longer periods and may require months to years for the LNAPL to gradually stabilise. The LNAPL distribution that accumulates in the subsurface is typically termed the 'source zone' of contamination. It comprises both immobile residual LNAPL, which is trapped in pore space by capillary forces, and potentially mobile LNAPL which exists as a continuous liquid across interconnected pores and is able to migrate when subjected to a sufficient driving head. The latter often manifests as a layer of LNAPL (e.g., oil or fuel) distributed across the water table-capillary fringe interface due to the LNAPL buoyant nature. Some penetration of LNAPL below that interface is, however, possible.

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. Some of these processes are conceptualised in Fig. 5.7 overleaf.

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.

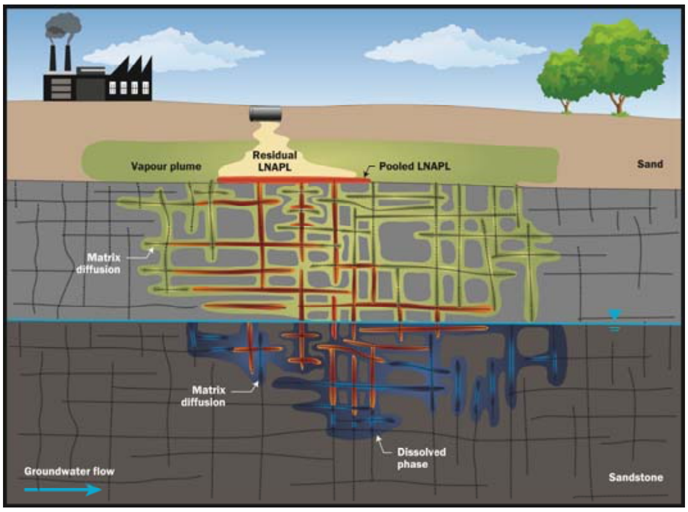


Figure 5.7 (extract from the LNAPL illustrated handbook). LNAPL release from cemented fractured sandstone.

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.

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*).

Table 5.1 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.

Table 5.1 (amended extract from the LNAPL illustrated handbook). Exemplar hydrogeological environments.

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

Section 5 of the LNAPL illustrated handbook further develops these various environments as annotated CSMs. The examples provided are specific to the exemplar hydrogeological environments tabulated. However, 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.

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.

There are two main drivers in the management of LNAPL-impacted sites that inform site characterisation needs:

- to understand the potential risks posed to receptors by both current and plausible future mobile LNAPL distributions, and the migration of their associated dissolved-phase and vapour-phase plumes; and
- to understand LNAPL constraints on remediation selection, design and operation which often requires more targeted investigation and pilot testing of the system.

If a potential source-pathway-receptor linkage (potential risk) is identified, characterisation is typically focused on the LNAPL source zone: the origin of any potential risk and frequent target for remedial action. Investigation aims to establish source zone distribution and chemical composition, and to identify pathways to potential receptors.

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.

LNAPL-impacted sites can pose a considerable technical and management challenge and the requirement for remediation may be driven by a range of concerns related to the presence of LNAPL itself and/or associated vapour- and dissolved-phase groundwater plumes and their potential impact to perhaps several receptors. The applicability and relative significance of each of these concerns and hence the focus of potential remediation will depend on the regulatory regime, the nature and extent of the LNAPL release, the site setting and the specific circumstances of a given site.

The LNAPL illustrated handbook was written by the following authors - Derek Tomlinson (Geosyntec Consultants), Steven Thornton (University of Sheffield), Alan Thomas (ERM), Stephen Leharne (University of Greenwich) and Gary Wealthall (Geosyntec Consultants) - and edited by Michael Rivett (University of Birmingham).

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The LNAPL illustrated handbook is available as a free download from the CL:AIRE website: www.claire.co.uk/LNAPL.