CRC for Contamination Assessment and Remediation of the Environment

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# Technical impracticability of further remediation for LNAPL-impacted soils and aquifers

D. Lam and P. Moritz

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**Enquiries and additional copies:**
CRC CARE, P.O. Box 486, Salisbury South, South Australia, Australia 5106
Tel: +61 (0) 8 8302 5038
Fax: +61 (0) 8 8302 3124
www.crccare.com

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# Executive summary

### Background

Petroleum hydrocarbons when released to soil and groundwater environments can lead to unacceptable risks, and remediation may be required. However, the point at which further remediation becomes technically impracticable for light non-aqueous phase liquids (LNAPLs such as petroleum fuels) in the subsurface is difficult to define. The extent of remediation that is technically possible is unclear as is the process for determining appropriate end points, for the range of subsurface conditions encountered in Australia.

Where a site is found by assessment to contain LNAPL on the groundwater remediation is usually implemented, whether voluntarily by the site owner, or under a regulatory requirement. Although there are broad descriptions of the concept of limiting practicability of remediation, there is little specific guidance available to site owners, remediators, site auditors or regulators as to what is the appropriate technical approach for remediation and, for that method, what tools or processes are available to define the point at which the system can be turned off. This often results in a complex and drawn-out closure phase – where the uncertainty results in repeated efforts at remediation through a phase of diminishing returns, where it is difficult to achieve agreement from stakeholders regarding the merits of further work, and where the net environmental benefit of further effort is unclear.

### Remediation in Australian conditions

Soils in major Australian population centres, where most LNAPL-impacted sites occur, are generally of low permeability, except in Perth, where sands predominate. Consequently groundwater is generally little-used in the eastern states as a major source for large-scale domestic water supply, while groundwater is a major resource in Western Australia.

The range of remediation technologies for LNAPL-impacted sites can be broadly categorised as:

- those that are effective in low-permeability soils which predominate in the eastern states, and
- those that are effective in coarser soils more common in Western Australia.

In high permeability soils, approaches like pump and treat and low vacuum SVE (soil vapour extraction) (together being low vacuum dual phase recovery) are more applicable, while in finer grained soils, MPE (multiphase extraction) is more likely to be effective for active LNAPL recovery. In the finer grained soils, LNAPL saturations will generally be lower and LNAPL mobility and recoverability will be limited to a small percentage of total LNAPL present. In coarser soils, LNAPL saturations will generally be higher, and mobility and recoverability of LNAPL will be higher.

The selection of technologies for remediation should be based on a screening process that includes consideration of factors including:

- technical
- logistical

- financial, and
- timing.

Remediation Action Plans (RAPS) should be seen as flexible, progressively developed documents that are updated from a conceptual stage, to account for results of piloting/trial works, and adjustment of the adopted strategy to ensure optimal application. The view that a RAP is a final document that can be applied without variation does not produce optimal outcomes.

Once a situation is reached in which LNAPL recovery rates are low using an initial technology, the remaining LNAPL may or may not warrant further remediation by alternative methods that have the potential to attack the remaining LNAPL.

### Process for remediating an LNAPL-impacted site

The following steps are suggested in order to ensure that a site is adequately characterised and then appropriately remediated:

1. Recognise the LNAPL problem.
2. Notify regulator immediately, in order to pro-actively engage them and ensure that any mutually agreeable end point is reached with the minimum of re-work.
3. Conduct any emergency response work that may be required if immediate/imminent risks are found.
4. Perform sufficient investigation works to provide a relatively complete conceptual site model of hydrogeological conditions and source-pathway-receptor linkages (may involve assessments of risk in order to determine remediation goals).
5. Prepare a conceptual RAP outlining:
    a) remediation objectives and end points, which may be based on quantity or concentration data (especially where a current risk is present), or built around the concept of diminishing (asymptotic) returns for the optimal remediation technology (where cleanup is not risk-driven)
    b) a technology screening matrix that identifies either a clearly preferred method for remediation trials/piloting, or a range of preferred methods for such evaluation.
6. Conduct remediation trials and update RAP (if no technologies are deemed to be practicable, based on the selected trials, and no others are considered to warrant further trialling, this should be documented along with the rationale).
7. Implement RAP to the agreed end points, whether prescriptive target conditions or based on diminishing returns (asymptotic recovery) arguments.
8. Submit outcomes to regulator/auditor.
9. Review residual risk.
10. Consider the need for any further remediation effort or, where risks are demonstrated to be contained, continue with monitoring and any required management.

In following the above approach, there must be recognition from all stakeholders of the following:

- Where risks to human health or the environment are current, remediation or management should be undertaken to mitigate the risk. The concept of Technical Impracticability of further LNAPL remediation should only be considered in the absence of ongoing unacceptable risk.
- In many aquifers, regardless of level of LNAPL remediation effort, it will rarely be possible to achieve total removal of LNAPL. In these cases, it is sensible to determine Technical Impracticability for further LNAPL remediation on the basis of multiple lines of evidence, including the following suggested remediation metrics:
  - LNAPL transmissivity (once decreased to a point indicating low mobility and recoverability),
  - LNAPL saturation remaining (once decreased to a point indicating low remaining LNAPL volume, mobility and recoverability),
  - LNAPL plume stability (indicating a lack of migration potential),
  - Dissolved COC stability (a de facto measure of LNAPL plume stability), and
  - Asymptotic cumulative recovery from remediation efforts (indicating a lack of mobility and recoverability).
- In some cases, even though LNAPL is detectable in wells, further recovery of LNAPL will be impracticable.
- Net environmental benefit should be considered for ongoing remediation.
- If the plume is stable, remediation efforts may not provide any benefit in terms of reduction of risk to human health or the environment.

The practicable limit for the remediation of LNAPL is an elusive concept, because no one answer applies to all sites, but if the above metrics are adopted and supported by field data and available tools such as models, it should be possible to determine a condition for site closure with respect to the active LNAPL remediation phase.

## Suggested further research

Suggestions for additional areas of research that may lead to a more comprehensive ‘manual’ style approach to defining the optimal approach to achieving remediation to the extent practicable for Australian conditions are:

- Development of a risk model to reflect changes in risk characterisation commensurate with varying levels of remediation effort.
- Further trials of remediation methods using multiple methods on site with significant LNAPL, in order to more fully document comparative performance of various technologies in Australian conditions, including those in the eastern states. This would ideally correlate field data against predicted modelled LNAPL conditions in terms of saturations and recoverability. If conducted, this would provide validation of the adoption of published models for use in Australian conditions.

# 1. Introduction

## 1.1 Background

Petroleum hydrocarbons when released to soil and groundwater environments can lead to unacceptable risks, and remediation may be required. However, what constitutes the point at which further remediation becomes technically impracticable for light non-aqueous phase liquids (LNAPLs such as petroleum fuels) in the subsurface is difficult to define. The extent of remediation that is technically possible is unclear as is the process for determining appropriate end points, for the range of subsurface conditions encountered in Australia.

Where a site is found by assessment to contain LNAPL on the groundwater, remediation is usually implemented, whether voluntarily by the site owner, or under a regulatory requirement. Although there are broad descriptions of the concept of limiting practicability of remediation in Australian guidance, there is little specific information available to site owners, remediators, site auditors or regulators as to what is the appropriate technical approach for remediation and, for that method, what is the point at which the system can actually be turned off. This often results in a complex and drawn-out closure phase, in which the uncertainty results in repeated efforts at remediation through a phase of diminishing returns, where it is difficult to achieve agreement from stakeholders regarding the merits of further work, and where the net environmental benefit of further effort is unclear.

Following the principles of the NEPM (Assessment of Site Contamination) 1999, it could be argued that there is a place, in determining technical impracticability of further remediation, for the use of more quantitative risk assessment. In this regard, the complexity of determining the end point for remediation is especially difficult, when considering the relative risk before and after remediation, at least for LNAPL plumes that are relatively old and stable. This is because experience in LNAPL remediation in many Australian conditions shows that even where LNAPL can be removed effectively at sites, after intensive efforts, there is almost always some LNAPL remaining that is extremely difficult to remove. In terms of reduction of mass flux and therefore risk from dissolution to a dissolved phase in groundwater, or volatilisation to vapour phase, the reduction of risk that is achieved may be limited. Of course, for recently released, mobile LNAPL plumes, there is an obvious benefit to remediating to a point at which residual saturation is reached, and the migration of the LNAPL body is arrested, but even this concept is not well defined in any specific guidance with regard to the technical impracticability of further remediation.

## 1.2 Project scope

The aim is to establish, as much as possible (recognising the difficulties of being too prescriptive), the technical limit to conditions under which LNAPL can be cleaned up from NAPL-impacted soils and aquifers, with some commentary on the perspective of stakeholders, including regulators, to place in context the determination of that limit. This embodies both the characterisation and behaviour of NAPL in the subsurface, its probable risks, and technologies that can achieve LNAPL recovery.

# 2. Site characterisation and LNAPL behaviour

## 2.1 Site characterisation – conceptual site model

Success or failure of an LNAPL remediation program depends to a large extent on the adequacy of site characterisation.

Site assessment for LNAPL sites is an area not covered in detail by this paper, however there is a range of tools for developing sampling strategies to characterise sites such that site conditions are well defined, and remediation planning can be initiated. A key tool in characterising an LNAPL plume is the conceptual site model (CSM). The ASTM *Standard Guide for Development of Conceptual Site Models and remediation Strategies for Light Non-Aqueous Phase Liquids Released to the Subsurface* (E2531-06) provides a framework for developing CSMs for LNAPL sites, and is complementary to the ASTM *Risk Based Corrective Action* guides (E1739 and E2081), and the ASTM standard for CSMs (E1689). The guide goes further than describing only the CSM for the site, and includes strategies for remediation based on the CSM. Requirements for a CSM are also described in the US EPA *Decision Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquid,* 2005.

The Standard Guide for LNAPL CSMs (LCSMs) is based on a tiered approach to LNAPL sites, following a similar approach to the RBCA standard.

The guide specifies firstly that immediate hazards be mitigated (such as the presence of explosive vapours or flammable liquids). This is an important point, in that it recognises the importance of mitigating immediate risks urgently, rather than deferring action until all data are available.

Following any required initial emergency response phase, the LNAPL presence should be assessed and a Tier 1 assessment of the adequacy of the CSM should be undertaken. This includes consideration of risk factors, hydrogeological and plume factors, and remediation factors.

At this stage, in following the guide, remediation actions may be implemented, if needed, or alternatively LNAPL objectives can be identified, and RBCA style tiered evaluation of risk drivers can be undertaken. Up to this point the LCSM guidance is risk-based, but the next stage recognises the possibility that non-risk based factors may be important, through relevant regulations and policy.

The LCSM guide then proceeds through the definition of remediation metrics, evaluation of remediation action alternatives (and use of a higher tier LCSM if appropriate), development of a remediation strategy, design and installation, monitoring of remediation, and finally long term site management. The development of higher tiers of LCSM is (where considered applicable) based on the use of more site specific information, such as:

- appropriate involvement of stakeholders and public consultation
- site specific risk information, and
- inability of any remediation alternative to address the site objectives.

In terms of the conceptual site model for the contamination and how it interacts with possible receptors, the LCSM factors, as noted split into the following key areas.

1. Potential risk factors – primarily the linkages of sources via pathways for migration to potential receptors, but also including consideration of business and community issues.
2. Hydrogeology and plume factors – in order to describe the likely fate and transport of various phases of contamination associated with the LNAPL release, including bothy aquifer properties and LNAPL properties.
3. Remediation factors including costs, challenges and uncertainties.

Once the conceptual site model is developed it is possible to identify the existing conditions, and how they are likely to change, and to identify current or potential future risks that require mitigation. The conceptual site model in respect of risks (in terms of exposure of receptors) can be expressed in text form but is also commonly described using plans and cross sections graphically depicting hydrogeological conditions and exposure pathways.

An important consideration in assessment and development of a CSM from which to proceed to the development of a Remediation Action Plan (RAP) is that investigations should be comprehensive enough for the purposes. For instance full lateral delineation of an LNAPL plume and associated dissolved phase impact is normally required before appropriate remediation options can be considered.

## 2.2 LNAPL behaviour

Discussion of the knowledge of LNAPL behaviour is critical to understanding the applicability of alternative remediation methods.

LNAPL behaviour has been described in many publications including the US EPA’s *Light Nonaqueous Phase Liquids – Ground Water Issue EPA/540/S-95/500* (1995) and in various publications by the American Petroleum Institute (API), which are summarised in API’s *Interactive LNAPL Guide* (2004). As well, much knowledge has been summarised in the USA-based Remediation Technologies Development Forum (RTDF) course notes *Understanding the Behaviour of Light Non Aqueous Phase Liquids (LNAPLs) in the Subsurface* (2005).

LNAPL when released into the sub-surface moves through the pore space in the unsaturated zone and, where sufficient LNAPL is released, will continue to migrate (generally) downwards and eventually accumulate around the water table. While early conceptualisations of LNAPL existence assumed LNAPL occupied all of the pore space in an assumed ‘pancake’ layer above the water table at the thickness represented in wells, it quickly became recognised that the amount of free product in the wells might not accurately represent the amount of LNAPL in the formation and a vertical exaggeration or apparent thickness correction factor became popular. It was however still assumed that pore spaces at the top of an unconfined aquifer were filled entirely with LNAPL, with assumptions of LNAPL volume and recoverability exaggerated. Many remediators made high predictions of recoverable LNAPL quantities but found that mobile, recoverable LNAPL was a small fraction of that predicted.

In 1990 research activities lead to the ‘multiphase’ conceptualisation, in which LNAPL coexists in the soil pores with water over a given thickness within the aquifer. In this representation, LNAPL saturation decreases with depth while water saturation increases with depth, in the zone where LNAPL is present on the water table, without there being a ‘hard’ border delineating water-filled and LNAPL-filled zones. This arises because the LNAPL displaces the water by pushing into the pore spaces of the upper portions of the saturated profile. With depth, the amount of LNAPL displacing water in the pores decreases until at some depth no water is displaced and the pores remain 100% filled with water (water saturation). When a well penetrates the LNAPL saturated soil, LNAPL and water will migrate into the well bore and the thickness of LNAPL in the well will reflect the thickness of the aquifer in which some amount of LNAPL saturation is present. Since water remains in some of the pore spaces (for some soil, the majority of the spaces), the amount of LNAPL in the formation is less than the monitoring well might suggest.

In the ‘multiphase’ conceptualisation, soil and product properties are important in defining the LNAPL saturation profile. If these site properties are well characterised and the apparent well product thickness is appropriately measured, the LNAPL profile in the aquifer can be predicted. The mobile LNAPL volume, LNAPL mobility, and LNAPL recoverability can be evaluated.

LNAPL plumes can be analysed using mathematical models. Spreadsheet-based models have been developed by Charbeneau et al. (1999) and Charbeneau (2003), and more complex numerical models for LNAPL evaluation include ARMOS (ES&T Software Ltd 1988) and UTCHEM (Delshad 1996). The API Interactive LNAPL guide and the more recent LNAPL Recovery and Distribution Model (LDRM) include spreadsheet-based calculation tools to allow for the estimation of LNAPL quantity per unit area of plume, a measure of $m^3$ of LNAPL per $m^2$ of plume area. This ‘specific volume’ of LNAPL provides a measure of LNAPL quantity, reflecting estimated saturations, and the variation of LNAPL saturation with elevation above the LNAPL/water interface, for differing soil types.

Because LNAPL saturations are only a proportion of the total pore space in the zone where some mobile LNAPL is present, estimates using current-day tools suggest LNAPL quantity, mobility and recoverability is significantly less than early (1980s) estimates would have suggested. For finer soils such as clays, the LNAPL saturation curve has a maximum of less than 10% of total pore space, meaning that over 90% of pore space is occupied by water or air, in the zone where mobile LNAPL is present. This leads to the estimates of the specific volume of LNAPL being very low in relation to the total volume of aquifer in which LNAPL is present, represented by the plume area and in-well LNAPL thickness. In clay soils, a measured in-well thickness of several m of LNAPL may equate to a total volume of LNAPL present, that if completely extracted and placed into a receptacle, would be only a few cm thick. This explains some of the difficulty in reconciling field observations of LNAPL presence with remediation expectations.

The mobility of LNAPL increases as the LNAPL saturation in the pore-space increases. Due to capillary forces, some LNAPL is always retained in the soil pores as residual or immobile LNAPL. The remaining ‘untrapped’ LNAPL is mobile and may continue to migrate. At the lateral fringes of an LNAPL body, and at the vertical limit of LNAPL presence (where there is little LNAPL and the pores are mostly water-saturated), the volume of mobile or ‘free’ product decreases as LNAPL becomes trapped as isolated droplets within the soil pore network. In these fringe parts of the LNAPL body, the LNAPL is effectively immobile unless there is sufficient ongoing migration from the primary source, or from the centre of the LNAPL body. Therefore LNAPL plumes, unless continually supplied from an on-going release have a finite limit on the extent to which the LNAPL plume can migrate, related to the soil properties (and groundwater gradients) in any given release situation. At some point in time, and at some lateral extent, an LNAPL plume will become stable and there will be no further LNAPL migration.

## 2.3 Soil properties

The properties of the soil affect the behaviour of LNAPL in the sub-surface. The size and connectivity of pores within the aquifer material affect the movement of fluids. The pore geometry of a soil is a function of the grain size of the particles and the arrangement of the particles. Soil type, which is based on the relative percentage of clay, silt, sand, and gravel-size particles, is a major factor that determines LNAPL mobility. Coarser soils have bigger pores, and greater permeability. Finer-grained soils (and those with a wider distribution in particle size (more ‘poorly sorted’)), such as occurs with clays, have smaller pores and lower permeability.

In finer grained aquifer materials such as silts and clays, migration of LNAPL is slower due to the reduced LNAPL permeability. But once LNAPL occupies the pore space in finer grained soils as a ‘free’ or ‘mobile’ product, a higher proportion is retained as ‘residual saturation’ (compared with coarser soils), due to the high capillary forces.

The potential for LNAPL to move is termed ‘inherent mobility’. It is a function of the properties of the soil and LNAPL and the relative LNAPL saturation. Mobility is controlled by the aquifer permeability, the viscosity of the product, and the relative LNAPL permeability, which is directly related to the LNAPL saturation. High LNAPL mobility occurs when low viscosity products occur in permeable soils at high saturations. Low mobility occurs for fine-grained soils with more viscous (generally heavier fraction) products at low saturations.

Australian soils are varied across the major population centres. These locations have relevance as they are the places with the largest number of petroleum-related facilities and the overwhelming majority of LNAPL contaminated sites. A generalised summary of soils types through these centres is presented below:

- Melbourne – weathered Silurian bedrock and Silurian clays and silts, and sedimentary sandy and silty clays; some areas of basalt and basaltic clays
- Sydney – Hawkesbury Sandstone, claystone/shale
- Adelaide – generally thick layers of clay soils underlain by variable weathered fractured bedrock
- Perth – sandy soils
- Brisbane – weathered rock.

In general, with the exception of WA and localised areas in all states, soil types across the main population centres in Australia have generally low permeability and do not have significant groundwater use in terms of the groundwater representing a major potable water source.

Therefore for many locations throughout the major population centres, the inherent mobility and recoverability of LNAPL plumes is relatively low. The result is that remediation programs in many areas, even where well designed and executed, are likely to result in some degree of LNAPL saturation remaining in the sub-surface.

Another effect of the soil types across the major population centres is that the typical soil types reflect the generally low utilisation of groundwater as a resource for domestic water supply across the main cities of Australia, with the obvious exception of Perth. There is local variation, with sandy (or similarly high permeability soil) deposits in sub-areas of all cities, with uses typically for market gardening, industrial water, and irrigation of parkland. Some areas of major cities have local low-yield bores that are used for lawn-watering, even where there is little potential for large scale groundwater extraction.

While many small towns and regional centres across the country do rely on groundwater for a substantial proportion of the total domestic water supply, this is not true of most of the capital cities.

In comparison, many cities in other parts of the world draw significant proportions of water supply (in some cases virtually all water) from groundwater resources.

This means is that there is a different level of overall risk between Australia and many overseas locations, with respect to remediating groundwater impacted by contamination such as that associated with LNAPL spills.

As a very brief summary, an LNAPL spill into an area with high permeability soils is:

a) more likely to migrate and impact a used groundwater resource, and

b) more likely to be able to be remediated to a relatively high-standard remediation requirement (e.g. little or no remaining LNAPL).

Conversely, an LNAPL spill in an area with low permeability soils is:

a) less likely to migrate and impact a used groundwater resource, and

b) less likely to be able to be remediated to a relatively high-standard remediation requirement (e.g. little or no remaining LNAPL).

## 2.4 Product types

Petroleum products are derived from the refining of crude oil. Refined petroleum products consist of hundreds of individual hydrocarbon compounds. These products have variable physical properties and chemical composition. Physically, the products are characterised by properties such as density, viscosity, boiling point, wettability, interfacial and surface tension, volatility, and solubility. Chemically, hydrocarbons are organic molecules composed of the elements hydrogen and carbon and are categorised into three types: cycloalkanes, aromatics, and straight or branched-chain alkanes.

The properties combine to mean that a product is either more or less likely to be able to be effectively recovered from the ground. In general terms, heavier (longer hydrocarbon chainlength), more viscous products tend to migrate less and be more difficult to recover once in an LNAPL plume.

Lighter, more volatile products pose a greater risk to human health through volatilisation into the vapour phase, which can then be inhaled, but are more readily recovered.

## 2.5 Release conditions

Release conditions in terms of the duration and rate of release, depth to groundwater, groundwater gradient, and so on combine with soil properties and product types to affect how the LNAPL will migrate and the degree to which it will be recoverable. The release conditions are also important to the degree of risk posed by the existence of the LNAPL plume.

In general terms, long term releases that allow for long-term migration from the primary source area will be difficult to remediate with any short-term remediation solution.

With shallow groundwater, an LNAPL release will relatively quickly reach the water table, and spread laterally. This can lead to the possibility that remediation options such as direct excavation may become viable, while those requiring isolation from short-circuiting (vacuum enhanced methods such as multi-phase extraction) become compromised. Shallow LNAPL plumes are also more likely to lead to human health risks where volatile LNAPLs are involved.

## 2.6 Mobility, stability and recoverability

LNAPL mobility is dependent on the degree of saturation, which is in turn dependent on LNAPL properties, release conditions and soil type. At residual saturation, LNAPL that is present is trapped within pores and will not flow by gravity. This situation eventually occurs when a release has ceased and an LNAPL plume has spread over time to a point where there is not remaining mobile LNAPL. Where the release is ongoing or recent, or where the groundwater has little gradient to facilitate LNAPL movement, such that the LNAPL has not yet spread out to a state of residual saturation, there will be LNAPL present in parts of the LNAPL plume that is locally above residual saturation. This LNAPL that is in excess of residual saturation is mobile, in that it will flow by gravity if sufficient gradient is present. This mobile LNAPL is sometimes called ‘free product’.

The concept of LNAPL mobility is important because it reflects the fact that with any remediation system that relies on gravity, there is a point at which virtually all of the LNAPL will be unrecoverable.

LNAPL stability is a term that relates to the plume-scale dynamics. For a given set of circumstances (soil type, product type, groundwater gradient and so on) an LNAPL plume (in the absence of ongoing release) will typically reach a maximum extent which does not further change over time.

Within a stable LNAPL plume, LNAPL on the edges of the plume area is at or below residual saturation, while locally in central parts of the plume; LNAPL may exceed residual saturation and still be recoverable by methods such as pumping. At the edges of an LNAPL plume, it can often be that virtually no LNAPL is able to be recovered by gravity methods.

There is a common misconception that residual saturation is always a very small proportion of total LNAPL, whereas, particularly in fine-grained soils, residual saturation may represent most of the LNAPL mass in a plume, with the recoverable (mobile) portion being a minority. In more coarse soils such as Perth sands, and with fresh releases, a much higher proportion of total LNAPL present in a plume may be mobile and therefore recoverable.

## 2.7 Water table fluctuations

Water table fluctuations have the effect of smearing the mobile LNAPL in an LNAPL plume, which more rapidly produces a state of residual saturation (in a smaller area) than might occur in the absence of such fluctuations. When the water table fluctuates, LNAPL presence as observed in monitoring wells can vary. Typically in periods of high water table, LNAPL observable in monitoring wells decreases, and increases again when the water table returns to a lower level. This can be observed on sites near the coast with tidal fluctuations in water table, and at other sites during periods of high groundwater recharge from rainfall.

## 2.8 Heterogeneous conditions

Soil heterogeneity often affects LNAPL migration. Preferential pathways for migration often follow zones of higher permeability, whether anthropogenic (service trenches and the like) or natural (such as sand lenses or other high permeability zones in otherwise low permeability soils).

LNAPL plume movement, and localised mobility and recoverability of the LNAPL will vary with the variable conditions.

In fractured rock, LNAPL presence is often confined to the fractures, with little contaminant presence in the limited primary porosity of the rock. These conditions can be challenging in terms of remediation, because recoverability from tight fractures can be difficult, particularly where fracture orientation and continuity are such that LNAPL has virtually no mobility under pumping.

## 2.9 Phase distribution

Where LNAPL is present in the subsurface, there is a constant exchange between various phases around the smear zone. The LNAPL itself, as noted above, will be present as a combination of residual saturation and mobile LNAPL. Some hydrocarbon will be sorbed to soil particles (not as LNAPL), some will be dissolved in pore water; and some will be volatilised into the vapour phase in pore air.

## 2.10 Volatilisation

Volatilisation of LNAPL represents one of the major issues for LNAPL management in Australia. Whereas in many cases the actual extractive use of groundwater may be limited by low yield or marginal salinity, such factors do not mitigate the risk to human health from volatilised contaminants from LNAPLs. This is particularly true for indoor air scenarios.

So while in many cases overseas the driver for remediation may be the protection of a current-day potable groundwater resource, in many areas of Australia, the key driver will more often be protection of site occupants from the inhalation pathway.

As well as risks to indoor air of buildings, there are potential risks to maintenance workers in services such as stormwater drains and deep sewers. Sewers are particularly vulnerable as they commonly leak (allowing ingress of hydrocarbon contaminants including vapours), and often present at depths of up to 6 m, and in some cases of tunnelled sewers, even deeper.

The pathway of volatilisation has relevance for remediation of LNAPLS with significant proportions of more volatile fractions, because this allows vacuum enhanced remediation methods such as soil vapour extraction (SVE) and multiphase extraction (MPE) to be adopted as a means to access recovery of LNAPL.

## 2.11 Dissolution and transport

LNAPL in contact with groundwater, or with percolating water in the unsaturated zone, will release constituent compounds into the water through the process of dissolution. This process allows contaminants from the LNAPL secondary source plume to migrate far further than may the LNAPL plume itself, in some circumstances.

The dissolved phase plume may represent a risk to receptors associated with any extractive groundwater bores (particularly in areas of high soil permeability and high usage of groundwater resources, such as in Perth sands). The dissolved plume may compromise ecosystems where the dissolved phase plume emerges at a surface water body. In some cases the dissolved phase plume may release vapours of significance to human receptors.

An important point is that residual saturation LNAPL has similar capacity to release dissolved phase contaminants to groundwater as does mobile LNAPL. Therefore the risk reduction produced by reducing the mobile LNAPL in a plume such that only residual saturation remains is mainly associated with:

- Reduction of total contaminant mass, which can lead to mechanisms such as natural attenuation occurring more rapidly, and
- Reducing the mobile LNAPL such that the maximum future LNAPL plume extent is limited.

In terms of remediation, because the dissolved phase is so slowly released, pumping of dissolved phase has proven to be generally ineffective as a means of remediating NAPL. Much of the case experience leading to this conclusion has been associated with DNAPL solvent plumes, but the same principle is true for LNAPLs. Pumping of dissolved phase emanating from a NAPL plume (whether LNAPL or DNAPL) has some effectiveness as a management measure, but has very limited effectiveness in remediating the LNAPL itself.

# 3. Remediation technologies

## 3.1 Remediation technologies

Descriptions of a range of technologies for LNAPL remediation (both for residual saturation LNAPL and mobile LNAPL), are described in many publications. Case studies of remediation applications are available through individual papers which are referenced, and through collected sets of remediation case studies such as the several hundred abstracts collected under the auspices of the US Federal Remediation Technologies Roundtable. The American Petroleum Institute Interactive LNAPL Guide includes a summarised description of many common LNAPL remediation technologies.

### *3.1.1 Bailing*

In hand bailing, LNAPL is lifted manually out of the well by a simple bailer and disposed. Costs are low.

Recovery is limited to the immediate area near the well, as there is no induced gradient or other mechanism such as vacuum pressure to induce LNAPL flow to the well, other than the very short-term small drawdown associated with the act of bailing. Once the well is emptied of LNAPL, LNAPL in the nearby formation will migrate into the well, depending on the degree of LNAPL mobility (faster for thick LNAPL in high permeability soils, slower for thin LNAPL in low permeability soils). Because of the limited capture area hand bailing is not an efficient recovery technology where a significant area is impacted or the mass of hydrocarbon needing to be recovered is large. However, the LNAPL to water ratio in recovered fluid is relatively high.

If remediation time is unimportant, hand bailing can be applied in less permeable formations, but as the radius of influence is negligible, an end point is not being expedited by using the method. Because of the limitations in recovery, bailing alone would rarely represent the practicable limit of remediation.

### *3.1.2 Well skimming*

Skimming wells recover LNAPL with little or no recovery of groundwater. Because groundwater is not recovered, skimming systems do not hydraulically control LNAPL plumes or induce gradients to speed up recovery. Therefore the radius of influence of any well is (as with bailing), small. This technology is applied where the LNAPL is mobile and the plume is stable. This situation may occur for instance with an LNAPL plume that is present in high permeability materials but contained and prevented from migrating by lower permeability materials. While efficient in terms of the ratio of LNAPL recovered to water recovered, the rate of recovery is slow, being limited by the inflow of LNAPL to wells without applied gradient or vacuum (Motsch et al. 2002). Skimming wells are generally more effective in permeable soils, such as sandy aquifers.

The costs generally low compared to other approaches to LNAPL removal. Types of equipment include floating skimmers with pneumatic pumps, passive bailer/filter canisters, and passive absorbent bailers/socks.

Well skimming – as with bailing - will remove only that proportion of the mobile LNAPL that happens to reach the well, without the encouragement of any applied gradient through pumping or vacuum. It has no impact on residual saturation LNAPL, either directly or through the dissolved or vapour phases.

### *3.1.3 Trench skimming*

In trench skimming systems, LNAPL is recovered from a series of wells/sumps contained within or at the ends of a constructed trench. The trench is constructed of coarse material (relative to the site soils) and located to intercept the groundwater and LNAPL flow. There may be little or no recovery of groundwater. Trenches can be designed to contain an LNAPL plume. This technology is applied where the LNAPL is mobile and the plume is migrating. Depending on how many trenches are constructed through a plume, the approach may be relatively active, or passive. As with skimming wells the rate of recovery is generally slow since product migration into the trench is controlled by the natural gradient, unless significant pumping is undertaken. It is limited to relatively shallow groundwater conditions where trench construction is practical, which is generally depths of less than 5 m. Trenches are often used in low-permeability aquifers and heterogeneous sites, which might otherwise require a large number of wells to control LNAPL flow.

The costs associated with this approach are generally moderate. Treatment costs may vary from minimal where there is negligible water recovery, to significant where there is significant water recovery.

Trench skimming will also remove only that proportion of the mobile LNAPL that happens to reach the trench, without the encouragement of any applied gradient through pumping or vacuum. It has no impact on residual saturation LNAPL, either directly or through the dissolved or vapour phases. The advantage over well skimming hand bailing is that a trench through an LNAPL plume accesses more of the LNAPL simply by being in contact with (or at least close to) more of the plume area.

### *3.1.4 Barrier walls with skimming*

Where containment is required, barrier walls with skimming or trench pumping systems may be suitable. A barrier wall is installed to contain the LNAPL or direct it towards specific outlets for recovery. Trenches operating as a downgradient migration barrier may incorporate a membrane on the downgradient side, vertically across the water table, in order to limit migration of any LNAPL or associated dissolved contamination through the barrier wall system.

There may be little or no recovery of groundwater; alternatively groundwater recovery can be significant, in order to contain dissolved contaminants and ensure that LNAPL does not bypass the barrier wall structure. Whether or not to include significant groundwater pumping depends on the remediation/containment needs. This approach is more of a ‘passive containment’, rather than ‘active’ system. LNAPL recovery is generally slow because product migration into the trench is controlled by the natural gradient. It is limited to relatively shallow groundwater conditions where a barrier wall in a trench can be constructed, which is generally depths of less than 5 m.

A barrier wall system will remove that proportion of the mobile LNAPL that happens to reach the barrier wall and be collected, without the encouragement of any significant applied gradient through pumping or vacuum. While the introduction of some pumping may draw LNAPL into the trench, this will typically only operate laterally out from the barrier over a small distance, and as barrier walls are generally not constructed through the central (high thickness/high mobility) parts of LNAPL plumes, this system does not actively draw in LNAPL other than that which would soon flow to the downgradient barrier alignment at the LNAPL plume fringe. In a circumstance where the LNAPL plume is effectively stable, a barrier may provide some degree of insurance that LANPL will not extend past a chosen alignment, but may not actively recover very much LNAPL. Depending on the circumstances, this may be a good initial solution for sites where ongoing losses are still being managed, but would need to be augmented by other more active methods through the LNAPL plume(s) in order to represent the practicable limit of LNAPL remediation. The introduction of some pumping does allow for the removal of dissolved phase, but this is as a by-product of controlling LNAPL bypass of the barrier, or for the direct minimisation of dissolved phase itself; the removal of dissolved phase does not significantly act to reduce LNAPL itself significantly.

### *3.1.5 Pump and treat*

In the API *interactive LNAPL Guide*, this technology is called ‘water table depression’. This remedial approach creates a cone of depression in the water table to induce an LNAPL gradient toward an extraction well. This approach is widely used and applicable where hydraulic control of a LNAPL and/or dissolved plume is necessary, because the induced gradient effectively limits further migration of LNAPL and associated dissolved contaminants.

LNAPL recovery via an induced gradient is practicable where LNAPL is highly mobile, such as for fresh spills in coarse soils (Kavanaugh et al. 1994). These systems can operate in a range of geologies, but are generally more cost effective in formations of high permeability – conditions that are uncommon in many Australian population centres.

For these systems, both product and groundwater are withdrawn from the recovery well. The LNAPL and water can be recovered separately (dual pumping) or as a combined fluid mixture (single pump). Single pump recovery wells are easier to install but may induce more difficulties in treatment as the pumping may create an LNAPL-water emulsion.

One factor in pump and treat methods is that hydraulic draw-down must be managed carefully. Attempts at large vertical draw-down in low permeability formations can result in limited mobile LNAPL recovery, with a significant proportion of LNAPL ending up as residual saturation in the intended drawdown cone (Moyers et al. 1997). Maintaining small drawdowns minimises this effect, but produces low rates of recovery and smaller radii of influence around recovery wells. In high permeability formations, significant drawdowns do not result from pumping as readily as in finer soils, and the ‘residualisation’ of LNAPL is less extensive (because of the nature of the coarser soils), so pump and treat can be a very effective containment/recovery strategy, especially for fresh spills and/or large quantities of LNAPLs. A reported case study from a former refinery at Sugar Creek (US EPA 2005) indicated that dual-pump recovery (a form of pump and treat) has worked very efficiently in sands with very high LNAPL saturations. In that instance, LNAPL recovery has proceeded over more than 20 years, and cumulative recovery is in the range of many millions of litres of LNAPL.

The cost of treatment of the produced groundwater may increase overall remedial costs, especially with high-rate recovery in high permeability soils. This can be particularly problematic in many Australian aquifers where salinity is high and may preclude ready disposal of treated water to sewer or even if treated to an appropriate standard with respect to COCs, to surface waters.

Single and dual-pump recovery systems are generally low to moderate in cost depending primarily on long-term treatment of co-produced water.

In summary, pump and treat has applicability, especially for very large spills and in coarse soils, but has limitations in lower permeability soils. The technology has applicability where establishment of hydraulic control and containment is a high priority.

Case studies show that asymptotic recovery of pump and treat can occur over periods from short duration, up to many years (as at Sugar Creek, as noted above).

### 3.1.6 Multiphase (vacuum enhanced) extraction (MPE)

MPE (also called MPVE) applies a vacuum to skimmer wells or induced water table gradient recovery wells to enhance LNAPL remediation. The system can be driven by a single recovery pump using well ‘stingers’ to entrain (slurp) fluids, as well as recover vapour, or may comprise separate fluid and air pumps (dual phase extraction (DPE)). In either pumping arrangement, the system induces a larger potential gradient toward the recovery well but minimises the physical movement of the LNAPL-water interface – thus minimising the smearing of mobile LNAPL to a state of residual saturation. Specifically, the vacuum induces a negative pressure, which causes upwelling of the LNAPL water interface, whereas the hydraulic recovery induces a positive gradient. As a result, the rate of hydrocarbon recovery is increased without introducing such a large smear zone as occurs with pure pump and treat recovery (Chan et al. 2005; Johnston et al. 2005; US EPA 1997).

MPE, is described as a presumptive remedy for VOCs in soil and groundwater (US EPA 1997). MPE is noted to be most efficient in low to moderate permeability soils, where high vacuums can be generated (Cushman et al. 2006). Very coarse soils prevent the ready generation of vacuum pressures in the sub-surface, although low vacuum DPE may still be implemented in coarse soils. DPE is a well established and effective technology for LNAPL contaminants (Motsch et al. 2002).

In general, conditions that predominate in many Australian population centres where LNAPL plumes occur are suitable for one form or other of MPE.

Evaluation of MPE usually focuses on the recovery of the hydrocarbon liquids through pumping. However air extraction also creates the potential for biodegradation in the vadose zone due to the enhanced delivery of atmospheric oxygen (Johnston et al. 2005). Such bioventing during multiphase extraction is often ignored when evaluating the overall removal of petroleum hydrocarbons.

Where the LNAPL largely comprises volatile fractions, the residual saturation LNAPL can be volatilised. Volatilisation is increased by changing the phase distribution equilibrium. Two mechanisms promote this:

- the negative pressure acts to produce a higher proportion of contaminant in the vapour phase, and
- the extraction of air draws in cleaner air from the plume fringes, promoting a concentration gradient that in turn allows more volatilisation of LNAPL.

While the removal of hydrocarbons other than in the mobile LNAPL phase (such as through bioventing and volatilisation in the vadose and smear zones) may not be the primary aim in remediating mobile LNAPL to the extent practicable, the reductions in residual saturation/adsorbed phase contamination in the smear zone allows subsequent residualisation of mobile LNAPL, for instance when smearing occurs due to water table fluctuations. This means that the removal of residual saturation can also act to reduce mobile LNAPL.

One factor that can compromise MPE is the presence of significant short-circuiting pathways. This may result in pilot testing revealing low available suction pressures with high air flows, and little vapour recovery. In such circumstances, sealing the short-circuit pathway could be attempted, or other methods such as pump and treat may be preferred. Soil heterogeneity also compromises the ability of MPE to remove LNAPL volumes as predicted by modelling (Adamski et al. 2005).

MPE costs are higher than less intensive recovery systems (such as pump and treat) and implementation can be expensive in medium to high-permeability soils. In addition, the treatment of the extracted vapour can be significant in some locations. The application of MPE may also be limited at sites with significant water table fluctuations.

Time is a significant factor in the application of MPE recovery systems. There are many applications of MPE technology using a short-term suction event from a mobile unit (often truck-mounted). Experience indicates that such events can be useful in cases where plume extents are very limited (such as where LNAPL is limited to underground tank pits, or very localised areas such as isolated fracture systems). On the other hand, in cases where LNAPL plumes have spread over a long period of time through low-permeability soils, recovery of such LNAPL is difficult to achieve with a short term system, and a long term operation is likely to be required.

As noted above in the description of Pump and Treat, in some circumstances, such as very large spill volumes in mainly coarse soils, MPE may not be preferable to Pump and Treat. As described, works at the former refinery at Sugar Creek (US EPA, 2005) indicated that dual-pump (pump and treat) recovery worked efficiently in sands with very high LNAPL saturations. Where MPE was trialled at the same site (although in a different area, with less permeable soils and much lower LNAPL saturations), LNAPL recovery was far less efficient. This, however, is a reflection of the differing soil types and release conditions as much as a comparison of the merits of the technologies.

Case studies indicate the asymptotic decay of recovery for MPE can occur within timeframes of up to two to three years for difficult sites (Adamski et al. 2005; US EPA 2005). A summary of eight case study sites in Canada using dual phase recovery cited times to asymptote of five to 30 months.

### *3.1.7 Hydraulic fracturing for the recovery of NAPL and contaminated groundwater*

Whilst not a stand-alone remediation method per se (rather, this is a method for amending the hydrogeology to conditions potentially more favourable for traditional remediation methods to be applied), this approach has been trialled by CSIRO. The summary by CSIRO Land and Groundwater is presented below:

> ‘Hydraulic fracturing in a fractured rock aquifer was investigated in a pilot-scale field trial to improve the remediation of spilled hydrocarbons. The objective was to increase the permeability of selected vertical intervals in the aquifer thereby improving the rates and efficiency of non-aqueous phase liquid (NAPL) petroleum hydrocarbon and contaminated groundwater recovery. It was aimed to increase permeability of the aquifer and radius of influence of pumping wells by increasing the number, horizontal extent and conductivity of fractures. The test involved hydraulic fracturing at a number of different intervals in the same hole and measuring the vertical displacement, ground surface tilt and pressures in the aquifer to elucidate the fracturing process. Permeability of the aquifer to both water and NAPL was compared before and after the fracture treatment including down-hole testing of the intervals fractured. Overall, the fracturing treatments were observed to increase the bulk water transmissivity of the aquifer to a distance of 11.5 m from the fracture hole. The fracture treatments also improved the lateral connectivity across the site. Individual treated intervals had permeability increased by as much an order of magnitude. However, there was also evidence that the proppant used decreased permeability of an interval of naturally high transmissivity.’

As described by Mostch et al. (2002), fracturing can be implemented using pneumatic and blast enhanced fracturing, as well as the hydraulic fracturing noted above.

The summary indicates that this approach may be worthwhile for consideration in some circumstances as an adjunct to traditional remediation technology application.

### *3.1.8 Excavate and treat or dispose*

Whilst perhaps not recognised as a remediation ‘technology’ per se, the option of excavating and treating or disposing soils containing an LNAPL plume may be considered as an option when conditions are suitable. Such conditions would generally require the water table to be shallow enough for ready access (less than say 5 m; preferably even shallower), and for the site to be clear, or able to be cleared without the loss of any buildings or structures being of consequence, and without destabilising any other structures.

Other factors include overall available site area in order to allow for management of clean overburden and management/treatment of impacted soils. A further factor to consider is the management of sub-areas of the site, and how to isolate and seal off excavated areas from non-excavated areas to avoid recontamination of ‘cleaned’ areas; particularly for high permeability soil sites. This may involve temporary clay walls and significant pumping and treatment or disposal of accumulated excavation water.

Ex-situ treatment options may be limited by constraints introduced by concerns over odours and associated vapour health risks, for both off-site parties and on-site workers. Some states apply limitations to site management practices that lead to the transfer of volatile contaminants into the atmosphere unless there are sufficient controls on atmospheric discharges, and it can be shown that the primary mechanisms for management of volatiles are treatment rather than release to atmosphere.

The advantage of excavation of an LNAPL plume is that the impact is directly removed from the impacted zone, although any option requiring off-site disposal without treatment would need to be considered in terms of any waste management hierarchy adopted by the relevant state regulator, as this approach would result in the use of significant landfill air-space. As well, any excavations into the top of the saturated zone would need to be carefully considered in terms of the management of resulting impacted water and LNAPL both accumulating in the excavation, and draining from excavated saturated soils.

### *3.1.9 Monitored natural attenuation*

Monitored natural attenuation (MNA) is a passive approach that depends on natural processes to dissipate and/or degrade petroleum constituents. These processes may include dilution, dispersion, volatilisation, biodegradation, adsorption, and chemical interaction with soils. Biodegradation is usually the most important natural attenuation process. In some cases due to the composition of the LNAPL or the site conditions (such as minimal groundwater flow/recharge), the residual product within the subsurface is relatively inactive. In these cases, the transfer of hydrocarbon mass from the LNAPL phase to the vapour phase or to the dissolved phase is very slow and natural processes within the subsurface are sufficient to degrade or dilute the concentrations close to the source. Such conditions may occur in weathered products and heavy fuels which have low volatility and solubility. In these cases, biodegradation may exceed the dissolution or volatilisation rate for the higher molecular weight compounds.

In some regulatory jurisdictions, MNA is not considered to be an active remediation method, and the expectation is that other more active methods would be attempted to the point of their practicability, and then MNA may be employed in the monitoring/management stage that follows.

The effectiveness of MNA is limited where hydrocarbon concentrations are large and the natural attenuative capacity of the subsurface is low. This typically occurs with fresh NAPL, such as motor spirit and diesel, or where groundwater velocities are relatively high to enable a high rate of transfer of mass from the LNAPL phase to the water phase.

Monitored natural attenuation is low cost as often the only investment is in sampling sentinel monitoring wells to ensure continued attenuation. For certain sites, it is a favourable remedial option and should always be considered, as it will form the final remedial technology at most sites.

MNA works primarily on the dissolved and vapour phases, with relatively little impact on the LNAPL directly.

### *3.1.10 Soil vapour extraction*

For readily volatilised petroleum liquids such as gasoline, soil vapour extraction (SVE) has been shown to be an effective technique for removing contamination from the vadose zone. However this technique is found to be ineffective in the capillary fringe and below the water table where the aquifer is liquid saturated (Johnson et al. 1990; Rathfelder et al. 2000; Smith et al. 1996).

SVE relies on the ability to generate vacuum over a radius of influence from the extraction well and so will be compromised in extremely coarse shallow soils (e.g. gravels) where vacuum cannot be maintained because of short-circuiting effects, or extremely low-permeability soils, where vacuum radius is small. SVE can work in fractured rock provided there is adequate connectivity and fracturing. Preferential pathways in otherwise suitable soils can compromise SVE. Studies have shown that it can be difficult to achieve complete remediation of NAPL sources due to complex entrapment of NAPL in heterogeneous soil systems (Wadugea et al. 2004).

SVE is represented in a number of case studies available through the US Federal Remediation Technologies Roundtable, and in the US EPA *Treatment Technologies for Site Cleanup: Annual Status Report.* SVE is commonly used in conjunction with groundwater pumping, as DPE, a form of multi-phase extraction.

SVE applied during multi-phase extraction was shown to be very effective at removing hydrocarbon mass from the vadose zone above the water table in sands near Perth (Johnston et al. 2001).

SVE works on the vapour phase, by providing a concentration gradient that allows LNAPL in the unsaturated zone to volatilise and be removed. SVE can be used to remove mobile LNAPL, but where the zone saturated by a mixture of water and LNAPL (excluding connected air-filled porosity) is thick, the removal of the LNAPL will be rate-limited, because the remediation is acting only on the upper ‘surface’ of the saturated zone. Where used without simultaneous pumping, SVE near the water table can be compromised by upwelling, where water can be drawn up to flood the zone in which there is some air-filled porosity in the smear zone (US EPA, 1997).

SVE is applicable in permeable soils and for LNAPL consisting of relatively volatile compounds.

SVE systems are low to moderate in cost.

Overall, SVE has limited applicability to reduce large thicknesses of LNAPL, but can be used in higher permeability soils and in conjunction with other technologies.

### *3.1.11 Air sparging*

Air sparging (AS) consists of the injection of air into the saturated zone of an impacted aquifer in order to enhance transfer of volatile compounds from LNAPL. The sparged air migrates through the smear zone and mass is transferred via the vapour phase into the rising air bubbles. At the water table, the vapours migrate to the unsaturated zone where an SVE system is generally used to collect the vapours.

Combining (AS) with SVE greatly improved the removal of gasoline petroleum hydrocarbons in a studied LNAPL–contaminated sandy aquifer scenario. AS increased the mass of petroleum hydrocarbons recovered by a factor of 1.9, and removed residual LNAPL source from below the water table (Johnston et al. 2001).

There is evidence that the radius of influence of influence can be relatively small in uniform aquifer materials and that channels can form within a close radius of the sparge well and that increasing sparge air flow rates increases the number of channels (Johnston & Davis 1997).

Air sparging is effective in homogeneous and permeable aquifers typical in Perth, but less common through eastern Australia. Stratified and les permeable soils more common in the eastern states limit the effectiveness and containment of the sparged air. Heavy products such as lubricating oils are not effectively remediated by this technology.

Air sparging is moderate to high in cost.

Sparging is not generally used where there is a large quantity of mobile LNAPL, as it is inefficient in such circumstances.

### 3.1.12 Enhanced bioremediation

In terms of LNAPL remediation, bioremediation is rarely used as a primary technology to degrade the LNAPL Body (US EPA 2005). However, technologies such as SVE, MPE or bioventing (effectively low-rate SVE) can be used to degrade residual LNAPL.

### 3.1.13 Other methods

Release of PSH entrapped below the water table can be enhanced by the introduction of surfactants. Experimental works have shown that a substantial portion of NAPL can flow through both fractures and permeable blocks, but that the fractures offer minimal NAPL storage following drainage and redistribution (Schwille 1981, 1988). Other experimental works with homogeneous materials (Powers et al. 1991) have shown that following redistribution the NAPL is eventually entrapped as disconnected ganglia. This can result in 20–50% of NAPL being trapped within porous media as a discontinuous material. Once mass transfer is achieved using surfactants the strategy employed is to remove the highly contaminated water (Chevalier 2003).

The use of surfactants to enhance NAPL solubility was reported to have improved treatment efficiency in terms of reduced treatment time and reduced treated water volumes for all simulated cases (Rubin et al. 2003). The use of surfactants to increase pumping velocity of NAPL by reducing interfacial tension between NAPL and groundwater is also reported (Chevalier 2003).

Other methods are available for remediation of LNAPLs, such as steam-stripping, chemical oxidation, in-situ thermal destruction, but these are not commonly used for LNAPL remediation and so are not considered further in this document. As new technologies become locally demonstrated, they should of course be considered for applicability. It is noted however that all stakeholders are usually reluctant to adopt a method that is not well known.

## 3.2 Summary of technical limits of remediation technologies

As noted in *API Bulletin Number 18* (Sale 2003), and in the US EPA *Decision Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquid*, as mobile LNAPL is removed from the subsurface, the diminished saturation of remaining mobile LNAPL means that the recovery rate (for any remediation technology) decays to an asymptote.

Based on the above review of well-demonstrated available methods of remediation, it is apparent that for many Australian situations, the limit of remediation effort for any LNAPL plume will be likely to leave in place some quantity of LNAPL which may be observable in monitoring bores.

One key issue for any remediation system is the need for the system to be progressively optimised throughout its operation. Any remediation system installed based on the best knowledge and intentions at the outset of remediation may not be the optimal system after some time. It may be that additional areas of plume become apparent that require attention, or operation modes such as periodic on/off phases may be beneficial, or options such as the use of passive air inlet wells may optimise recovery (Hultzer et al. 1989), particularly towards the end of an initial productive phase, where returns for effort are diminishing. Unless such efforts at system optimisation are attempted, it may be difficult to justify that all technically practicable efforts have been applied to any particular site.

Of the methods available for mobile LNAPL, bailing, well skimming, and trench skimming will all have potential to remove only a limited proportion of the mobile LNAPL. In such circumstances, no matter how much recovery of mobile LNAPL is undertaken, it is likely that monitoring wells within even a stable plume will continue to show measurable thicknesses of LNAPL.

Pump and treat methods produce greater LNAPL recovery via induced hydraulic gradient, and so may recover more of the mobile LNAPL. Pump and treat may be, in higher permeability soils or other situations where vacuum cannot effectively be produced, the only method applicable for recovering significant mobile LNAPL. Pump and treat may be the best method for remediation where LNAPL saturations are very high and LNAPL thickness is great. Pump and treat will also be useful for implementing hydraulic control, where that is the primary goal.

Multi-phase extraction allows both mobile LNAPL recovery per the pump and treat method, with the possibility of greater mobile LNAPL recovery (where high vacuums can be achieved) and some residual saturation LNAPL removal by volatilisation (where NAPLs contain significant volatiles) and enhanced biodegradation. As noted, the removal of residual LNAPL in the smear zone is likely to mean that remaining mobile LNAPL in the plume will be taken up in replacing the removed residual LNAPL in the smear zone. In this regard, this approach is, for many Australian low to medium permeability soils likely to warrant consideration. However, even in ideal circumstances, it is likely based on case study experience, that while a situation of asymptotic recovery may be reached, LNAPL may remain observable in monitoring wells.

Depending on the need to remove relatively thin LNAPL plumes, technologies such as sparging/SVE may be applicable.

A very general summary of the broad applicability of the major active *in situ* remediation technologies for various soil types is presented in Table 1 below, based on the review of various literature sources.

**Table 1. Summary of broad applicability *in situ* remediation technologies for various soil types**

| **Technology** | **Soil type** | | | |
|---|---|---|---|---|
| | High permeability soils (e.g. sands and gravels) | Low to medium permeability soils (e.g. clayey sands to silts) | Low permeability soil (clays) | Fractured rock |
| Pump and treat * | √√ | √ | x | √√ |
| SVE | √√ | √ | x | √√ |
| SVE/AS | √√ | x | x | x |
| Low-vacuum DPE | √√ | √ | x | √√ |
| MPVE (high vacuum) | x | √√ | √√√ | √√ |

** Pumping based technologies may be compromised by high salinity groundwater, because of difficulties in disposing of saline waste streams.*

## 3.3 Technology selection approach

Discussion on the concept of the limit of practicable remediation, where documented in Australia (such as in EPAV publication 840), notes a requirement to consider a range of factors in determining the practicability of any further remediation. These factors are:

1. technical
2. logistical
3. financial, and
4. timing.

Technology selection should be based on a selection or short-listing approach that takes into account the technical, logistical, financial and timing factors. Technical factors should include consideration of the site hydrogeology and conceptual site model, and LNAPL characteristics, and how that affects the applicability of the various technology options.

This approach can be done by applying a matrix of factors against technology options, to assign an overall selection ranking, in order to assess the overall best remediation option.

## 3.4 Remediation action plan

Key in demonstrating that remediation, where implemented, has been logically based and effectively used, is to have a documented remediation action plan (RAP). In Australia, the requirements for a RAP in terms of specific contents are described in the NSW EPA *Guidelines for Consultants Reporting on Contaminated Sites* (1997).

The RAP should précis all assessment knowledge of an LNAPL-impacted site, detail the remediation goals, and incorporate the rationale for selection of the proposed technology for any site.

The US EPA *Decision Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquid* (the Framework) describes a process for managing LNAPL-impacted sites, which recognises the complex technical challenges posed by LNAPL problems, and the associated financial commitments required to address those challenges, especially for larger, more complex sites. The Framework calls for planning for LNAPL management (including remediation) to be documented in an 'LNAPL Management Plan', which is described as a living document that can be revisited at various stages of the (LNAPL management) process. For instance, the Framework suggests a phased approach, with initial planning being based on a long-term vision for a particular site, and with realistic timeframes and cleanup budgets being determined by a range of stakeholders. In this regard, the management plan is not intended to be a fully detailed prescriptive plan, with all details for future works assumed to be known. Rather, it recognises that the process is progressive and that the plan will require amendment and updating over the long term as management proceeds.

# 4. Remediation outcomes – technical versus stakeholder expectations

While this paper focuses on the term 'technical' limit of practicable remediation, there is, in determining what 'practicable' means, interplay between site owners (and their consultants) and regulators (and auditors appointed or accredited by the regulators).

Definition of the meaning of the term 'Limit of Practicable Remediation' is important. Of the states, only Victoria currently has a formal definition of the limit of practicable remediation, where it describes 'Clean Up to the Extent Practicable', or 'CUTEP'. This term applies to all groundwater pollution, i.e. it is not limited to LNAPL. The CUTEP concept is defined in the Victorian EPA Publication 840 – *The Clean Up and Management of Polluted Groundwater* (April 2002).

From one perspective, the *technical* limit of practicability could be a considered to be a condition independent of subjective views of various stakeholders, and their varying value judgements on factors such as cost, timeframe and net environmental benefit. However, when this perspective is considered in the extreme, it can be argued that purely on a 'technical' basis, and with no limit to resources or time, it is always possible to recover some additional LNAPL on an LNAPL-impacted site. But this possibility to recover some minimal additional mass with considerable additional effort may well not be 'practicable', because of those other factors, and the value judgements that various stakeholders place on them.

## 4.1 Australian regulatory position

In order to assess the approach of various regulators across the country, they were approached for views on what their approach was to this concept as it relates to LNAPL remediation.

Questions asked were as follows:

1. What is the regulatory requirement for clean-up/remediation of LNAPL on groundwater?
2. How is this set:
    - by policy/regulation/legislation?
    - by guidance prepared by the regulator?
    - on a site by site basis by the regulator?
3. Is it based on inputs (i.e. prescribed actions or processes which must be undertaken) or on outcomes (achieving defined objectives)?
4. How is practicability defined or set?  How is it assessed?
5. What represents the end point?
6. What objective measures of practicability are used?
7. What are the objectives for LNAPL clean-up?  Who or what sets these?

8. Who determines that the practicable extent of clean-up has been achieved? Who, if anyone, puts the case that it has been? What is the burden of proof?
9. From a technical perspective, how do you know the end point has been achieved? Who or what sets out what can be achieved technically? What sources of information or references do you use in reviewing technical arguments about the practical limits?
10. What guidance do you publish about clean-up of LNAPL?
11. In making a decision, what discretion does the decision-maker have? Where do you strike the balance between what is written/published in guidance and the individual circumstances of any site?
12. What ongoing management will be required when the practicable extent of clean-up has been achieved?

The responses are summarised in Appendix A, and the key issues are more briefly summarised below.

### *4.1.1 Regulatory requirements for LNAPL*

All states except Queensland have specific requirements for the clean-up of LNAPL in groundwater. In Queensland, LNAPL is treated as any other contaminant affecting land and associated groundwater.

Where there is specific provision for clean-up of LNAPL, the clean-up objectives vary from state to state. In New South Wales, clean-up to the extent practicable is required. In Victoria, clean-up is required to the extent that the LNAPL is removed or it can be shown that there is no unacceptable risk to any beneficial use of the groundwater. However, clean-up to the extent practicable is also relevant, given that there is a general provision for this relating to other groundwater contaminants. In Western Australia and Tasmania, LNAPL clean-up is required, but to agreed end points rather than to the extent practicable.

### *4.1.2 Legislation and guidelines*

Victoria has a specific legislative instrument, the *State Environment Protection Policy (Groundwaters of Victoria) 1997*. This policy is pursuant to the *Environment Protection Act 1970*, and contains the provisions referred to above regarding LNAPL and Clean Up to the Extent Practicable.

Both New South Wales and Western Australia have specific Acts of Parliament dealing with contaminated sites and, by extension, groundwater contamination. These are the *Contaminated Land Management Act 1997* (NSW) and the *Contaminated Sites Act 2003* (WA).

Both Queensland and Tasmania have general provisions in their principal environmental protection acts which are used to deal with groundwater contamination by LNAPL. In Tasmania, this is the *Environmental Management and Pollution Control Act 1994,* and in Queensland the *Environmental Protection Act 1994* and the *Integrated Planning Act 1997*.

In all states, regardless of the legislative framework which sets out what must be done to manage pollution of groundwater by LNAPL, the provisions are outcome-focused. That is, there are objectives set for protection of the environment which represent clean-up targets of one type or another. None of the requirements for clean-up is prescriptive in setting what a site owner or remediator is to do in order to achieve clean-up.

In several states there are published guidance documents covering the clean-up of LNAPL. These are listed in Table 2 below:

**Table 2. Published guidance documents for the clean-up of LNAPL**

| State | Guidance documents |
|---|---|
| NSW | *Guidelines for the Assessment and Management of Groundwater Contamination* (March 2007) |
| Vic | EPA Information Bulletin *The Clean Up and Management of Polluted Groundwater* (April 2002)<br>EPA Information Bulletin *Groundwater Quality Restricted Use Zone* (July 2002) |
| Qld | None specific |
| SA | Site Contamination – Guidelines For The Assessment And Remediation Of Groundwater Contamination (February 2009) |
| WA | Contaminated Sites Management Series – *Use of Monitored Natural Attenuation for Groundwater Remediation* (April 2004) |
| Tas | None specific |

### *4.1.3 Regulatory objectives for LNAPL clean-up*

In New South Wales, LNAPL must be removed to the extent practicable. Where complete removal is impracticable, ongoing monitoring and management is required for as long as there is NAPL present. In Victoria, LNAPL must be removed, unless the EPA is satisfied that there is no unacceptable risk to beneficial uses of groundwater posed by the remaining NAPL. In addition, the objective for LNAPL removal can also be stated in terms of Clean Up to the Extent Practicable which is provided for in the *State Environment Protection Policy (Groundwaters of Victoria) 1997*, although this is seen as a secondary objective, used when it becomes apparent that the primary objective of LNAPL removal cannot be met.

In the other states, risk-based, site-specific target levels are used to set objectives for clean-up. In Tasmania and Western Australia these are set or agreed by the regulator. There may also be other objectives, based on longer term monitoring once these targets are achieved, designed to ensure that there is not a rebound effect some time after active remediation is completed. Western Australia requires at least two years of groundwater monitoring to validate remediation has been successful, and the DEC provides the sign off that clean-up has been completed. In Tasmania, achievement of end point is judged by a clearly decreasing trend in monitoring results and no further effect of remediation.

In Queensland, the Third Party Reviewer provides certification that the site-specific objectives have been met. In South Australia, following the Victorian Environmental Auditor system, an assessment of the practicability of NAPL remediation is reliant on the outcomes of an independent auditor (in the majority of cases) in direct consultation with EPA officers.

Practicability is considered by both New South Wales and Victoria to include technical, financial and logistical considerations. Often the practicable limit can be seen as the rate of LNAPL removal reaching an asymptote. However, in Victoria at least, such a situation also needs to be accompanied by an assessment that other remediation approaches are not capable of achieving further effect.

Determining that clean-up to the extent practicable has been achieved rests with the EPA in Victoria (apart from very limited circumstances), based on a submission (usually) from an Environmental Auditor. In New South Wales, and where the site is regulated by the Department of Environment and Conservation (DEC), decisions on clean-up to the extent practicable are verified by DEC, after a case has been made by the site owner or remediator.

Overall, the requirements set by state regulators for LNAPL remediation can in some cases be very prescriptive targets, but more usually the end point is described by the phrase ‘extent practicable’, which allows for judgement and negotiation.

### *4.1.4 Environmental Auditor perspective*

Auditors appointed or accredited to conduct contaminated site auditing are currently the practitioners who are submitting documented opinions on the status of contaminated sites, in the context of whether or not any further remediation of LNAPL is practicable. Several auditors were therefore asked to provide their views on how they reach their decision about the practicability of LNAPL remediation.

Their responses are summarised in Appendix B. The key points are more briefly summarised below.

Auditors cited the following indicators to assess the practicability of further LNAPL remediation:

- asymptotic recovery rates and LNAPL thickness
- mass balance based on LNAPL recovered versus identified quantities in the ground
- drop off in degradation rates and indicators of biological activity ($O_2$ consumption and $CO_2$ generation both decrease)
- residual attenuative capacity
- use co-solvent flushing as a diagnostic tool
- lateral extent of the plume.

It was recognised that complete removal of LNAPL was not considered likely in many cases.

Indicators for impracticability of further remediation included the abovementioned asymptotic recovery, with other factors being auditors did not consider that published guidance was prescriptive in terms of what actions should be undertaken or what an end point to practicable remediation should be.

### 4.1.5 Summary of regulatory position

The overall position is that regulators across Australia see that LNAPL, where present, must be actively remediated at least to ‘the extent practicable’. The expectation is that physical attempts are made to remediate in order to reduce what is perceived to represent an ongoing source of dissolved phase groundwater pollution and (for LNAPLs containing volatile components) vapours.

Regulatory guidance contains little discussion of actual measurable or quantitative estimated risk – from a regulatory (and auditing) perspective, LNAPL is considered to represent an unacceptable environmental condition and so must be removed, as much as it can be.

Some of this requirement to undertake remediation to the extent practicable, whether or not there is a current demonstrated risk, is a result of uncertainty about possible future beneficial uses of groundwater. For instance, in the Victorian *State Environment Protection Policy (Groundwaters of Victoria) 1997*, there is a principle outlined of ‘intergenerational equity’, the underlying premise of which is that the condition of the environment that is passed down to future generations should not be degraded. As well, the stated ‘precautionary principle’ states that the lack of full scientific certainty should not be used as a reason to postpone measures to prevent environmental degradation. Combined, these principles tend to mean that regulators are more prone to require remediation of contaminants including LNAPLs and related dissolved contaminants whether or not there is a clear current risk.

Regulatory guidance contains no exact definition of the end point of remediation for LNAPL.

A common theme in some responses regarding the end point for practicable remediation was the observation of asymptotic recovery rates of contaminant mass from the remediation effort. In this sense, there seemed to be an acceptance that an end point could be defined in terms of relative return for effort, rather than on what contamination remained. An exception was Western Australia, where the response suggested that it was expected that remediation would proceed to a determined site-specific remedial goal, although it was noted within the Western Australia response that specific reference was made to this being reasonable because of the nature of Western Australia’s generally sandy soils, in which remediation could be more successfully conducted than in other less permeable soils.

There was some discussion about the need to be flexible in terms of remediation methods tried. For instance, it was suggested that more than one remediation method could be attempted, in order to demonstrate that no further remediation was practicable.

## 4.2 Concept of net environmental benefit

The limit of practicable remediation depends on factors described earlier that include logistics, time and cost, as well as technical considerations. These considerations, which are built into existing guidance (for example, Victorian and NSW EPA guidance on groundwater contamination management), reflect the concept of net environmental benefit. This net environmental benefit assesses the value of proceeding with remediation effort which may produce no real reduction in risk, but carries significant time and resource cost. Running pumps, maintaining systems, producing streams of water requiring treatment, and contributing greenhouse gas emissions, must be balanced against tangible benefit for the effort. This consideration is reflected in the ASTM *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface*. This guide suggests that in evaluating the various remedial technologies applicable to the site, the success in attaining the stated objectives in terms of remediation metrics should be considered as 'benefits' in terms of a scoring system. On the other hand, 'costs' include the monetary cost, as well as any negative aspects associated with implementation of the remediation, such as waste stream generation, impairment of the site and adjacent properties, and safety issues. Many of the costs are related to timeliness of remediation.

Expectations of the community tend to be that if there is any contamination it should be removed completely, however this approach does not recognise that the costs to achieve such a condition may be (overall) environmentally worse that the original condition. Regulatory approaches, while recognising the need for balance in considering needs for remediation, tend to allow for the precautionary principle to be applied, so that some serious attempt at LNAPL remediation is usually expected, regardless (in the first instance) of considerations of quantifiable risk.

Ultimately this means that a remediation outcome is likely to be a compromise of expectations, as much as a particular, technically describable status for any site.

A compromise position may be that in order to see at least an attempt at serious remediation of LNAPL plumes, a primary technology should be employed or at least piloted/trialled for most sites where significant LNAPL is present, and implemented where results indicate that LNAPL is likely to be removed to significant effect (such as, to remove a significant mass, or to reduce the mobility of remaining LNAPL by reducing saturations to below residual saturation). The converse would be that where pilot-trial results indicate the remediation of significant LNAPL will not be achievable, even in the presence of significant measurable well thicknesses of LNAPL, alternative measures to active engineered remediation, such as MNA with monitoring at a downgradient compliance zone, may instead be warranted.

## 4.3 Risk reduction from LNAPL remediation

Where LNAPL is remediated, there is an argument that this always reduces risk associated with the plume, as the contaminant mass that may contribute to dissolved or vapour phase contamination is reduced. On the other hand, there is an argument that because it is rare to be able to remove all LNAPL, dissolved and vapour phases will be likely to continue to emanate from the remaining plumes for effectively similar long-term periods. Huntly and Beckett, in their paper *Persistence of LNAPL Sources: Relationship Between Risk Reduction and LNAPL* note that the risk to receptors (based on the downgradient extent of the dissolved phase plume) is generally unrelated to the longevity of the LNAPL plume. This is because the time in which the dissolved phase plume expands is generally a very small period when compared with the life of most LNAPL plumes.

Whilst remediation in coarse-grained soils or in intermediate soils with high LNAPL saturations may reduce the longevity of downgradient dissolved-phase contamination, in many cases involving finer grained soils and lower LNAPL saturations, risk reduction from LNAPL remediation can be negligible or non-existent. This challenges the view that holds that the presence of LNAPL itself represents a risk that will always be reduced by active remediation.

## 4.4 Groundwater management

As part of any remediation program, termination of remediation efforts requires definition of requirements for:

- ongoing risk mitigation
- monitoring
- trigger conditions for renewed action
- contingency actions for the situation where trigger conditions are reached (such as the reappearance of significant LNAPL).

# 5. Remediation metrics

## 5.1 Remediation end point

Many documents discuss the conditions which describe the point where further remediation can be considered impracticable. Examples include the US EPA *Guidance for Evaluating the Technical Impracticability of Groundwater Restoration*, and *A Decision Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquid*; the ASTM E2531-06 – *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous Phase Liquids Released to the Subsurface*; and API Research Bulletin Number 18 – *Frequently Asked Questions About Managing Risk at LNAPL Sites*.

Overall though, none of the guidance provides any specific measure of purely technical conditions that represent the threshold of technical impracticability.

The US EPA *Guidance for Evaluating the Technical Impracticability of Groundwater Restoration* does not offer specific guidance on end points for remediation. Rather, it recognises that groundwater restoration to specific clean-up targets can be limited by a range of site-specific factors. The guidance requires 'an evaluation of the restoration potential of the site, including data and analyses that support any assertion that attainment of ARARs (Applicable or Relevant Appropriate Requirements) or media clean-up standards is technically impractical from an engineering perspective'. Whilst this appears to point to a specific set of objectively-defined circumstances in which impracticability could be determined, the guidance notes that the analyses need to be done on a site-specific basis, and include factors such as timeliness, cost, and possible applicability of alternative technologies. With respect to cost, for instance, the guidance notes that a 'remedy alternative may be determined to be technically impracticable if the cost of obtaining ARARs would be inordinately high'. It goes on to describe that the point at which costs would be considered 'inordinately high' must be determined 'based on the particular circumstances of the site'. The guidance refers to the noted occurrence of asymptotic conditions during remediation, and the need for 'professional judgement (to be) applied carefully when drawing conclusions concerning restoration potential from this information'. In short, the guidance calls for a balanced argument presenting technical data, results of any remediation attempted, a requirement for alternative technologies to be considered, and details of cost and timelines to achieve further remediation outcomes.

The more recent document entitled *Decision Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquid* (US EPA 2005) offers a number of example end points for LNAPL remediation, as follows:

- 'Recovery rate is reduced to an established values (eg., three gallons per day);
- Specific COC (contaminant of concern) in LANPL is reduced to a target value at "x" monitoring locations over "y" period of time;
- Stability of the dissolved-phase plume is demonstrated based on a dissolved COC-concentration threshold at "x" monitoring locations over "y" period of time;

- LNAPL transmissivity is reduced to a certain value at “x” monitoring locations;
- LNAPL saturations at all points within the area of distribution have been reduced to levels below residual saturation, as measured by “a” method and cross-checked with “b” method;
- Groundwater samples from “XX” monitoring wells did not contain LNAPL-related organic constituents at concentrations above drinking-water maximum contaminant levels (MCLs) for four consecutive quarterly monitoring events;
- LNAPL chemistry has been changed so it no longer contains VOCs at measurable concentrations using analytical method “d” and vapour concentrations in the vadose zone measured by method “e” are below measurable levels;
- A containment system meeting “g,h,i” specifications has been installed and tested for integrity; and
- Final relative permeability value is attained.’

The ASTM *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous Phase Liquids Released to the Subsurface* notes that risk-based remediation metrics are relatively easily defined (for instance, it is easy to describe the required concentrations to meet a drinking water standard), but that metrics associated with non-risk factors ‘such as… practicable recovery requirements … may be more difficult to specifically define’. The guide notes that it (the guide) is intended to assist the user in ‘determining LNAPL remediation that is effective and efficient at a specific site’. It goes on to say that ‘Since “effective” and “efficient” are subjective terms, the user must identify the specific remediation metrics that pertain to the LNAPL site objectives and the evaluated remedial actions’.

The API Research Bulletin Number 18 – *Frequently Asked Questions About Managing Risk at LNAPL Sites*, by Sale (2003), notes that a decision on when to stop remediation in the face of declining recovery rates is related to the asymptotic LNAPL recovery curve. There is no specific condition in terms of a fixed percentage of original mass, or production rate, that applies universally to describe the limit of practicable LNAPL remediation, for any particular technology. The bulletin simply notes that a number of methods may be employed. As noted in the bulletin, as mobile LNAPL is recovered (by whatever technology), the remaining mobile LNAPL becomes harder and harder to recover. As described in the bulletin, idealised physics suggest that because of the asymptotic conditions, it would take an infinite time to reduce recovery rate to zero. It is also noted that owing to the complex relationship between the thickness of LNAPL in a well and the volume of recoverable LNAPL in the formation, LNAPL often remains in wells after recovery has diminished to ‘inconsequential rates’. A suggested end point is the achievement of 95% of the recoverable mobile portion of the LNAPL, beyond which further (infinite duration) recovery will not substantially alter the total amount of LNAPL (mobile and residual) left in place. It is noted that while estimates may be made of LNAPL saturation and degree of mobility, for any given plume, based on site data, ultimately the measure of recoverability is the cumulative recovery curve once optimised remediation is undertaken.

The US Interstate Technology & Regulatory Council (ITRC) is a US-based, state-led coalition of regulators, consultants, stakeholders and academics. Their stated goal is to work to achieve regulatory acceptance of innovative environmental technologies. Their paper, *Seeing The Forest Beyond the Trees* (2006), describes suggested metrics for remediation measurement, as reproduced below:

- ‘Operational metrics for engineered systems (e.g., fluid extraction rates, treatment system efficiencies, discharge requirements)
- Risk-reduction metrics (e.g., plume stability or recession, product or soil, removal, and land-use controls)
- Response completion metrics or site closeout criteria (e.g. Remediation Action Objectives (RAOs), confirmatory monitoring requirements).’

These measures are consistent with those suggested from other sources.

In summary, the literature provides no prescriptive measure for defining the end point for practicable remediation of LNAPLs, for any applicable technology. However, a number of remediation metrics are suggested that can be used to assess the value of ongoing LNAPL remediation. These are:

- LNAPL transmissivity
- LNAPL saturation (a measure of mobility)
- LNAPL plume stability
- Dissolved COC stability (a de facto measure of LNAPL plume stability)
- recovered LNAPL volume compared with predicted recoverable volumes based on models (e.g. Charbeneau 2003, via API), and
- asymptotic cumulative recovery.

The last measure (asymptotic recovery) would need to be used in the context that the selected remedial approach is optimal for the site.

Where risk reduction is achieved, this could be used as a remediation metric; but in reality, most cases of LNAPL remediation result in limited risk reduction, or elements of risk reduction (such as arresting of LNAPL plume migration) can be related to the other factors associated with LNAPL presence.

Regardless of which metrics are used, all assessments of the measures would need to include consideration that total recovery of LNAPL is virtually impossible, particularly for finer-grained soils. This may mean that for some sites with old, stable plumes, with low LNAPL transmissivity because all LNAPL is at residual saturation, there will be virtually no hydraulically recoverable LNAPL. It may be that in such cases no LNAPL remediation action is practicable, even though some LNAPL is measurable in wells.

# 6. Conclusions

## 6.1 Approach to reaching a mutually agreed end point for LNAPL remediation

This is the series of steps that are envisaged for the achievement of an agreed outcome on a site with an LNAPL plume, from the point of view of the site owner.

1. Recognise an LNAPL problem.
2. Notify regulator immediately, in order to pro-actively engage them and ensure that any mutually agreeable end point is reached with the minimum of re-work.
3. Conduct any emergency response work that may be required if immediate/imminent risks are found.
4. Perform sufficient investigation works to provide relatively complete conceptual site model of hydrogeological conditions and source-pathway-receptor linkages (may involve assessments of risk in order to determine remediation goals).
5. Prepare a conceptual RAP outlining:
    a) remediation objectives and end points, whether this be in terms of a set of concentration or quantity objectives, or built around the concept of diminishing (asymptotic) returns for the optimal remediation technology
    b) a technology screening matrix that identifies either a clearly preferred method for remediation trials/piloting, or a range of preferred methods for such evaluation.
6. Conduct remediation trials and update RAP (if no technologies are deemed to be practicable, this should be documented along with the rationale).
7. Implement RAP to the agreed end points, whether prescriptive target conditions or based on diminishing returns (asymptotic recovery) arguments.
8. Submit outcomes to regulator/auditor.
9. Review residual risk.
10. Consider the need for any further remediation effort or, where risks are demonstrated to be contained, continue with monitoring and any required management.

In following the above approach, there must be recognition from all stakeholders of the following:

- Where risks to human health or the environment are current, remediation or management should be undertaken to mitigate the risk. The concept of Technical Impracticability should only be considered in the absence of existing unacceptable risk.

- In many aquifers, regardless of level of LNAPL remediation effort, it will rarely be possible to achieve total removal of LNAPL. In these cases, it is sensible to determine technical impracticability for further LNAPL remediation on the basis of multiple lines of evidence, including the following suggested remediation metrics:
    - LNAPL transmissivity
    - LNAPL saturation remaining
    - LNAPL plume stability
    - dissolved COC stability (a de facto measure of LNAPL plume stability), and
    - asymptotic cumulative recovery from remediation efforts.
- In some cases, even though LNAPL is detectable in wells, recoverability of LNAPL will be impracticable.
- Net environmental benefit should be considered for ongoing remediation.
- If the plume is stable, remediation efforts may not provide any benefit in terms of reduction of risk to human health or the environment.

The practicable limit for the remediation of LNAPL is an elusive concept, because no one answer applies to all sites.

## 6.2 Suggested further research

Suggestions for additional areas of research that may lead to a more comprehensive ‘manual’ style approach to defining the optimal approach to achieving remediation to the extent practicable for Australian conditions are:

- Development of a risk model to reflect changes in risk characterisation commensurate with varying levels of remediation effort.
- Further trials of remediation methods using multiple methods on site with significant LNAPL, in order to more fully document comparative performance of various technologies in Australian conditions, including those in the eastern states.

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# APPENDIX A.

## Summary of questionnaire responses from regulators

In order to assess the approach of various regulators across the country, they were approached for views on what their approach was to this concept as it relates to LNAPL remediation.

Questions asked were as follows:

1. What is the regulatory requirement for clean-up/remediation of LNAPL on groundwater?
2. How is this set:
   - by policy/regulation/legislation?
   - by guidance prepared by the regulator?
   - on a site by site basis by the regulator?
3. Is it based on inputs (i.e. prescribed actions or processes which must be undertaken) or on outcomes (achieving defined objectives)?
4. How is practicability defined or set? How is it assessed?
5. What represents the end point?
6. What objective measures of practicability are used?
7. What are the objectives for LNAPL clean-up? Who or what sets these?
8. Who determines that the practicable extent of clean-up has been achieved? Who, if anyone, puts the case that it has been? What is the burden of proof?
9. From a technical perspective, how do you know the end point has been achieved? Who or what sets out what can be achieved technically? What sources of information or references do you use in reviewing technical arguments about the practical limits?
10. What guidance do you publish about clean-up of LNAPL?
11. In making a decision, what discretion does the decision maker have? Where do you strike the balance between what is written/published in guidance and the individual circumstances of any site?
12. What ongoing management will be required when the practicable extent of clean-up has been achieved?

The responses are briefly summarised below.

### *What are the regulatory requirements for clean-up/remediation of LNAPL on groundwater?*

LANPL is treated differently across the states, reflecting the states' different approaches to the management of land and groundwater contamination.

All states except Queensland have specific requirements for the clean-up of LNAPL in groundwater. In Queensland, LNAPL is treated as any other contaminant affecting land and associated groundwater. In South Australia, contaminated groundwater should be restored to meet the requirements and criteria of the SA EPA Water Quality EPP and/or background concentrations, but because this state has also adopted elements of the Environmental Auditing system in Victoria, those parts of that system which relate to LNAPL apply to some extent in South Australia.

Where there is specific provision for clean-up of LNAPL, the clean-up objectives vary from state to state. In New South Wales, clean-up to the extent practicable is required. In Victoria, clean-up is required to the extent that the LNAPL is removed or it can be shown that there is no unacceptable risk to any beneficial use of the groundwater. However, clean-up to the extent practicable is also relevant, given that there is a general provision for this relating to other groundwater contaminants. In Western Australia and Tasmania, LNAPL clean-up is required, but to agreed end points rather than to the extent practicable.

### *How is the regulatory requirement set?*

Only Victoria has a specific legislative instrument dealing with groundwater, the *State Environment Protection Policy (Groundwaters of Victoria) 1997*. This policy is subordinate legislation, pursuant to the *Environment Protection Act 1970*, and contains the provisions referred to above regarding LNAPL and Clean Up to the Extent Practicable.

Both New South Wales and Western Australia have specific Acts of Parliament dealing with contaminated sites and, by extension, groundwater contamination. These are the *Contaminated Land Management Act 1997* (NSW) and the *Contaminated Sites Act 2003* (WA). These have general provisions for the protection of groundwater, but specific requirements regarding LNAPL are contained in Guidelines prepared pursuant to the respective Act. In New South Wales, these are the *Guidelines for the Assessment and Management of Groundwater Contamination* (March 2007). Western Australia has a collection of guidance documents, the Contaminated Sites Management Series, and the guideline relevant to LNAPL is *Use of Monitored Natural Attenuation for Groundwater Remediation* (April 2004).

Both Queensland and Tasmania have general provisions in their principal environmental protection acts which are used to deal with groundwater contamination by LNAPL. In Tasmania, this is the *Environmental Management and Pollution Control Act 1994,* and in Queensland the *Environmental Protection Act 1994* and the *Integrated Planning Act 1997*.

In all states, regardless of the legislative framework which sets out what must be done to manage pollution of groundwater by LNAPL, the provisions are outcome-focused. That is, there are objectives set for protection of the environment which represent clean-up targets of one type or another. None of the requirements for clean-up is prescriptive in setting what a site owner or remediator is to do in order to achieve clean-up.

In several states there are, or soon will be, published guidance documents covering the clean-up of LNAPL. These are listed below. These guidelines go beyond what must be done to manage groundwater pollution, and incorporate information on how to meet regulatory obligations.

| State | Guidance documents |
|---|---|
| NSW | *Guidelines for the Assessment and Management of Groundwater Contamination* (March 2007) |
| Vic | EPA Information Bulletin *The Clean Up and Management of Polluted Groundwater* (April 2002)<br>EPA Information Bulletin *Groundwater Quality Restricted Use Zone* (July 2002) |
| Qld | None specific |
| SA | Site Contamination – Guidelines For The Assessment And Remediation Of Groundwater Contamination (February 2009) |
| WA | Contaminated Sites Management Series – *Use of Monitored Natural Attenuation for Groundwater Remediation* (April 2004) |
| Tas | None specific |

### *What are the objectives for LNAPL clean-up? What are the indicators that they have been achieved?*

In New South Wales, LNAPL must be removed to the extent practicable. Where complete removal is impracticable, ongoing monitoring and management is required for as long as there is NAPL present. In Victoria, LNAPL must be removed, unless the EPA is satisfied that there is no unacceptable risk to beneficial uses of groundwater posed by the remaining NAPL. In addition, the objective for LNAPL removal can also be stated in terms of Clean Up to the Extent Practicable which is provided for in the *State Environment Protection Policy (Groundwaters of Victoria) 1997*, although this is seen as a secondary objective, used when it becomes apparent that the primary objective of LNAPL removal cannot be met.

In the other states, risk-based, site-specific target levels are used to set objectives for clean-up. In Tasmania and Western Australia these are set or agreed by the regulator. There may also be other objectives, based on longer term monitoring once these targets are achieved, designed to ensure that there is not a rebound effect some time after active remediation is completed. Western Australia requires at least two years of groundwater monitoring to validate remediation has been successful, and the DEC provides the sign off that clean-up has been completed. In Tasmania, achievement of end point is judged by a clearly decreasing trend in monitoring results and no further effect of remediation. The responsible person or their specialist consultant sets out what can be achieved technically in making their case that the end point has been achieved.

In Queensland, the Third Party Reviewer provides certification that the site-specific objectives have been met. In South Australia, following the Victorian Environmental Auditor system, an assessment of the practicability of NAPL remediation is reliant on the outcomes of an independent auditor (in the majority of cases) in direct consultation with EPA officers.

Practicability is considered by both New South Wales and Victoria to include technical, financial and logistical considerations. Often the practicable limit can be seen as the rate of LANPL removal reaching an asymptote. However, in Victoria at least, such a situation also needs to be accompanied by an assessment that other remediation approaches are not capable of achieving further effect. It is not sufficient to consider just one remedial option. However, the alternatives need not be trialled or implemented to demonstrate that they would not be effective. A desk-based assessment can suffice to demonstrate this.

Determining that clean-up to the extent practicable has been achieved rests with the EPA in Victoria (apart from very limited circumstances), based on a submission (usually) from an Environmental Auditor. In New South Wales, and where the site is regulated by the Department of Environment and Conservation (DEC), decisions on clean-up to the extent practicable are verified by DEC, after a case has been made by the site owner or remediator.

### *In making a decision, what discretion does the decision maker have?*

While several states have published guidance on the clean-up objectives for LNAPL and the decision making processes to approve or verify clean-up, there is scope within those processes to take account of site-specific circumstances and site-specific risk assessments.

The New South Wales and Victorian guidelines acknowledge that decisions will depend on site-specific circumstances. In practice, the consideration of site-specific factors plays a major part in the determinations made by regulators. EPA Victoria will have regard to its published guidance, but the wide range of factors which can vary from site to site means that the decision making process can be lengthy. In those cases where the regulator sets the remediation end point at the start of the process, regulatory discretion comes into play at this stage, in determining that the risk-based objectives proposed are appropriate.

# APPENDIX B.
## Summary of questionnaire responses from auditors

Auditors appointed or accredited to conduct contaminated site auditing are currently the practitioners who are submitting documented opinions on the status of contaminated sites, in the context of whether or not any further remediation of LNAPL is practicable. Several auditors were therefore asked to provide their views on how they reach their decision about the practicability of LNAPL remediation.

Questions asked were as follows:

1. What objectives do you work toward in LNAPL clean-up?
    - from regulatory perspective
    - from a technical perspective.
2. How clearly are the regulator’s clean-up requirements set out?
3. To what extent is LNAPL clean-up dealt with on a site by site basis?
4. From a technical perspective, how do you know the end point has been achieved?
5. Who or what sets out what can be achieved technically?
6. What sources of information or references do you use in reviewing technical arguments about the practical limits?
7. What quantitative or objective indicators do you look for in order to assess the progress of clean-up and the limit of practicability?
8. In circumstances where you need to think about the limit of practicability of clean-up, how do you assess the likely practicability of further effort?
9. If site-specific targets have been set or agreed by a regulator, how do you address the situation where they are not met, and there is no statutory provision such as CUTEP (such as in Western Australia or Queensland)?
10. What discretion does the regulator give you in deciding that LNAPL clean-up need go no further?
11. As an auditor, what role do you play in the implementation of LNAPL clean-up? How far can you push the limits, either by what you will or you won’t endorse?
12. How clear is the published guidance (if any) that the regulator produces or offers?
13. Does this provide a technical limitation to what you can do to clean-up LNAPL?
14. What scope do you have to implement innovative approaches to the clean-up of LNAPL?

Their responses are summarised below.

### *What objectives do you work toward in LNAPL clean-up from a technical perspective?*

Where possible, get the LNAPL down to a minimal thickness (1–2 mm was quoted by the respondents) as a primary objective.  Secondary objectives, such as a low or asymptotic recovery rate, and drawing LNAPL back from the site boundaries were also mentioned.

### *How clearly are the regulator's clean-up requirements set out?*

Guidance varies widely from state to state. Where it is published it sets out objectives to be achieved. Site-specific guidance sets out end points to be achieved. None of the respondents reported prescriptive guidance which stipulated what had to be done.

### *To what extent is LNAPL clean-up dealt with on a site by site basis?*

LNAPL clean-up is always considered on a site-specific basis; it is not formulaic. However, understanding the conceptual site model, and having a rigorous model, is important to ensure that the correct approach is being taken. There is a strong expectation, either explicit or implicit, that some water quality objectives (or NEPM GILs) will be met.

### *From a technical perspective, how do you know the end point has been achieved? Who or what sets out what can be achieved technically? What sources of information or references do you use in reviewing technical arguments about the practical limits?*

The absence of a sheen is not sufficient, of itself, to indicate complete removal, as residual saturation LNAPL may remain. Unless additional steps are taken, complete removal cannot be said to have occurred. Such steps may include:

- solvent co-flooding
- use of surfactants
- groundwater ionic strength change, or
- accelerated attenuation.

An appropriate end point can be measured as recovered volume as a function of LNAPL layer thickness, although judgement is required as to when this indicates the end point. In addition, the nature of the underground system (aquifer type, soil characteristics, salinity, degree of fracturing) needs to be properly understood. In some cases complete removal can be achieved, but in others, this is most unlikely.

### *What quantitative or objective indicators do you look for in order to assess the progress of clean-up and the limit of practicability?*

- asymptotic recovery rates and LNAPL thickness
- mass balance based on LNAPL recovered versus identified quantities in the ground
- drop off in degradation rates and indicators of biological activity ($O_2$ consumption and $CO_2$ generation both decrease)
- residual attenuative capacity
- use co-solvent flushing as a diagnostic tool
- lateral extent of the plume.

***In circumstances where you need to think about the limit of practicability of clean-up, how do you assess the likely practicability of further effort?***

If the RAP has only one technical approach, look for the asymptotic decay of recovery rate and if there is a step wise approach, with different techniques applied, there will be a series of asymptotes. It may require three or four attempts/approaches to actually reach the end. However, having done this, there will be multiple lines of evidence that the practicable limit has been reached.

There needs to be flexibility built into the site infrastructure to ensure that more than one approach can be tried.

***What discretion does the regulator give you in deciding that LNAPL clean-up need go no further?***

There is very little discretion. The process is generally outcome driven, but the targets tend to be non-negotiable.

***As an auditor, what role do you play in the implementation of LNAPL clean-up? How far can you push the limits, either by what you will or you won't endorse?***

Use the assessor's or auditor's experience base to determine the technical limits. Conversely, the auditor's experience or lack thereof may be an impediment in trying new ideas.

***How clear is the published guidance (if any) that the regulator produces or offers? Does this provide a technical limitation to what you can do to clean-up LNAPL? What scope do you have to implement innovative approaches to the clean-up of LNAPL?***

Published guidance does not pose a limitation on innovation, especially as the process is outcome driven. There is a bigger limitation due to the limited number of options available.

## Summary of positions of regulators and auditors

The overall impression provided by the responses is that regulators and auditors across the country see that LNAPL, where present, must be actively remediated to the extent practicable. The expectation from these parties is that physical attempts are made to remediate in order to reduce what is perceived to represent an ongoing source of dissolved phase groundwater pollution and (for LNAPLs containing volatile components) vapours. The responses contained little discussion of actual measurable or quantitative estimated risk; it appears that the consideration from a regulatory and auditing perspective is that LNAPL itself represents an unacceptable environmental condition and so must be removed, as much as it can be.

Some of this requirement to undertake remediation to the extent practicable, whether or not there is a current demonstrated risk, is a result of uncertainty about possible future beneficial uses of groundwater. For instance, in the Victorian *State Environment Protection Policy (Groundwaters of Victoria) 1997*, there is a principle outlined of ‘intergenerational equity’, the underlying premise of which is that it is possible that the condition of the environment that is passed down to future generations should not be degraded. As well, the stated ‘precautionary principle’ states that the lack of full scientific certainty should not be used as a reason to postpone measures to prevent environmental degradation. Combined, these principles tend to mean that regulators are more prone to require remediation of contaminants including LNAPLs and related dissolved contaminants whether or not there is a clear current risk. An example of the type of concern that has been expressed by regulators is that what may be considered today to be a low-yielding aquifer with marginal salinity, and therefore of little obvious value, may be in an increasingly dry climate of the future be a more valuable short-term resource (Stuart McConnell, EPAV, pers. comm.).

There were no definitive statements about the definition of the end point of the remediation of LNAPL. Some references were made to a risk-based approach, but this was not expanded to state for instance that a risk argument would reasonably be used to obviate the need for at least attempts to remediate LNAPL. A number of references were made to the need for site-specific considerations.

A common theme in some responses regarding knowing what represented the end point for practicable remediation was the observation of asymptotic recovery rates of contaminant mass from the remediation effort. In this sense, there seemed to be an acceptance that an end point could be defined in terms of relative return for effort, rather than on what contamination remained. An exception was Western Australia, where the response suggested that it was expected that remediation would proceed to a determined site-specific remedial goal, although it was noted within the Western Australia response that specific reference was made to this being reasonable because of the nature of Western Australia’s generally sandy soils, in which remediation could be more successfully conducted than in other, less permeable, soils.

There was some discussion about the need to be flexible in terms of remediation methods tried. For instance, it was suggested that more than one remediation method could be attempted. This is interpreted to represent the requirement to be reasonably certain that the methods actually adopted are optimal in terms of having the best chance of achieving mass removal. Clearly, failure of an inappropriate method of remediation is not seen as a good rationale for representing that clean-up (or further clean-up) is not practicable.

CRC CARE Pty Ltd
ACN 113 908 044
University of South Australia
Mawson Lakes
South Australia 5095

P.O. Box 486
Salisbury South
SA 5106
Australia

**Tel:** +61 (0) 8 8302 5038
**Fax:** +61 (0) 8 8302 3124
**Email:** admin@crccare.com
**Web:** www.crccare.com

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