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# Standard Guide for NAPL Mobility and Migration in Sediment – Conceptual Models for Emplacement and Advection [1]

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## 1. Scope

1.1 This guide is designed for general application to a wide range of sediment sites where non-aqueous phase liquid (NAPL) is present or suspected to be present. This guide describes multiple emplacement mechanisms that can result in NAPL presence within the sediment stratigraphic profile and how the characteristics of the sediment, aquatic environment, and NAPL properties influence NAPL movement within sediments. This guide provides example conceptual models for NAPL emplacement in sediments in order to establish a common framework that can be used to assess conditions influencing NAPL movement by means of advection.

1.2 This guide supplements methodologies for characterization and remedial efforts performed under international, federal, state and local environmental programs, but does not replace regulatory agency requirements. The users of this guide should review existing information and data available for a sediment site to determine applicable regulatory agency requirements and the most appropriate entry point into and use of this guide.

1.3 ASTM standard guides are not regulations; they are consensus standard guides that may be followed voluntarily to support applicable regulatory requirements. This guide may be used in conjunction with other ASTM guides developed for assessing sediment sites.

1.4 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1689 Guide for Developing Conceptual Site Models for Contaminated Sites
E1739 Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites
E2081 Guide for Risk-Based Corrective Action
E2531 Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface
E3163 Guide for Selection and Application of Analytical Methods and Procedures Used during Sediment Corrective Action

## 3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *immobile NAPL*—NAPL that does not move by advection within the connected void spaces of the sediment under specified physical and chemical conditions, as may be demonstrated by laboratory testing, or may be interpreted based on mathematical calculations or modeling.

3.1.2 *in situ deposited NAPL (IDN) sediments*—NAPL-containing sediment resulting from the deposition of Oil-Particle Aggregates (OPAs).

3.1.3 *migrating NAPL*—NAPL that can move at the NAPL body scale, such that the NAPL body may advectively expand in at least one direction under observed or reasonably anticipated field conditions.

3.1.4 *mobile NAPL*—NAPL that may move by advection within the connected void spaces of the sediment under specific physical and chemical conditions, as may be demonstrated by

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

laboratory testing, or as may be interpreted based on mathematical calculations or modeling.

3.1.5 *NAPL*—Chemicals that are insoluble or only slightly soluble in water that exist as a separate liquid phase in environmental media.

3.1.5.1 *Discussion*—NAPL may be less dense than water (Light Non-Aqueous Phase Liquid [LNAPL]) or more dense than water (Dense Non-Aqueous Phase Liquid [DNAPL]).

3.1.6 *NAPL advection*—the process of NAPL movement in the subsurface due to pressure and gravitational forces.

3.1.7 *NAPL body*—Sediment where the NAPL present exhibits movement.

3.1.7.1 *Discussion*—The NAPL is mobile at the pore scale and either stable or migrating at the NAPL body scale. The NAPL body excludes any portion of the NAPL zone where the NAPL is immobile at the pore scale.

3.1.8 *NAPL emplacement*—the process by which NAPL is set in, or enters, sediment by either advective forces or by *in situ* deposition (IDN) through the water column.

3.1.9 *NAPL movement*—Any process where NAPL exhibits advective flow at any scale within the sediment; NAPL movement includes NAPL mobility at the pore scale and NAPL migration at the NAPL body scale.

3.1.10 *NAPL zone*—sediment where NAPL is present in any state; the NAPL can be mobile or immobile at the pore scale, or stable or migrating at the NAPL body scale.

3.1.11 *oil-particle aggregate (OPA)*—a particle formed in a surface water body resulting from the adherence to an oil droplet by minerals and/or organic material.

3.1.12 *pore scale*—the scale of the connected void spaces within the sediment.

3.1.13 *sediment*—a matrix of pore water and particles including gravel, sand, silt, clay and other natural and anthropogenic substances that have settled at the bottom of a tidal or non-tidal body of water (E3163).

3.1.14 *stable NAPL body*—NAPL that does not move at the body scale, such that the NAPL body will not advectively expand in any direction under observed or reasonably anticipated field conditions.

## 4. Significance and Use

4.1 Understanding the potential emplacement and transport mechanism for NAPL in sediment is an important element of an overall conceptual site model (CSM) that forms a basis for *(1)* investigating the nature and extent of NAPL, *(2)* evaluating if (and how) human and ecological receptors may be exposed to NAPL, and *(3)* assessing remedial alternatives. In addition, demonstrating the potential movement of NAPL in sediments to regulators and other stakeholders has been historically hampered by the lack of standardized terminology and characterization protocols. The complexity of NAPL movement in sediment, and the lack of agreed upon methods for analysis and interpretation of site data, has led to uncertainty in corrective action decision-making. This has sometimes resulted in misleading expectations about remedial outcomes. The emplacement and transport mechanisms for NAPL in sediments are different from those in upland environments, due to a variety of physical, geochemical, and biological differences between sediment and upland environments, thus necessitating this guide.

4.2 This guide is intended to supplement the CSM developed according to the principles outlined in the contaminated sites conceptual site model Guide E1689, the standard guide for developing a CSM for Light Non-Aqueous Phase Liquid (LNAPL) sites Guide E2531, and the Risk-Based Corrective Action (RBCA) Guides E1739 and E2081, by considering conditions for NAPL emplacement and movement (that is, advection) that are unique to a sediment environment. This guide will aid users in understanding the unique and fundamental characteristics of sediment environments that influence the occurrence and behavior of NAPL in sediments. Understanding the sources of NAPL encountered in sediment, the mechanisms for NAPL to become emplaced in sediments, and the site characteristics that influence the advective movement of NAPL within the sediment column will aid in identifying specific data requirements necessary to investigate these conditions and to provide a sound basis for remedy decisions.

4.2.1 Advective transport is the primary NAPL migration mechanism that is addressed within this guide.

4.2.2 In addition to advective transport, biogenic gas bubbles moving through sediments (that is, ebullition) may also facilitate NAPL migration; however, this process is beyond the scope of this guide.

4.2.3 Processes associated with NAPL movement due to erosion (for example, propwash) are not within the scope of this guide.



4.3 This guide describes the emplacement mechanisms and advective processes, and identifies the relevant information necessary for a technically reliable and comprehensive CSM in support of the investigation and/or remediation of NAPL in sediments. A technically reliable and comprehensive CSM will result in more efficient and consistent investigation of NAPL in sediments (for example, assessment of risks associated with NAPL in sediment, and/or remedy decisions). The key elements in assessing the presence and mobility of NAPL in sediment include *(1)* the hydrological setting, *(2)* the physical and chemical characteristics of the sediment, *(3)* the physical and chemical characteristics of the NAPL, and *(4)* the physical extent of the NAPL zone. The means and methods for collecting this information, including evaluating the mobility of NAPL in sediments, is not addressed in this guide.

4.4 Many contaminants (for example, chlorinated solvents, petroleum products and creosote) enter the subsurface as an immiscible liquid, known as NAPL. NAPLs may flow as a separate phase from water. If the NAPL is denser than water (known as dense non-aqueous phase liquid, or DNAPL), it will sink under the influence of gravity. If the liquid is less dense than water (known as a light nonaqueous phase liquid, or LNAPL), it will float on water.

4.5 This guide provides a logical framework for the initial assessment of NAPL movement in sediment environments. It will help users understand the physical conditions and emplacement mechanisms that influence NAPL movement and aid in prioritizing methods for gathering data to support development of a CSM.

4.5.1 The elements of a CSM for NAPL at sediment sites describe the physical and chemical properties of the environment, the hydraulic conditions, the source of the NAPL, the emplacement mechanisms, and the nature and extent of the NAPL zone. The CSM is a dynamic, evolving model that will change through time as new data are collected and evaluated and/or as physical conditions of the site change due to natural or engineered processes. The goal of the CSM is to describe the nature, distribution, and setting of the NAPL in sufficient detail, so that questions regarding current and potential future risks, longevity, and amenability to remedial action can be adequately addressed.

4.5.2 The unique elements for a CSM for a NAPL sediment site (compared to an upland NAPL site) include, but are not limited to:

*(1)* Characteristics of the sediment and water body.

*(a) Physical characteristics*: hydrology (for example, river currents, tidal conditions), sedimentology (for example, native water body bottom characteristics, deposited sediment characteristics, sedimentation rates, erosive forces), and hydrogeology (for example, groundwater-surface water interactions).

*(b) Geochemical:* for example, redox conditions

*(c) Biological characteristics:* for example, presence of benthic community

*(2)* Characteristics of the NAPL release(s) including sources, mechanisms, and timing unique to surface water and sediment that affect the conditions under which the NAPL was emplaced in the sediment.

*(3)* Mechanisms of NAPL emplacement in sediments, which include:

*(a)* Advective transport from upland sources,

*(b)* Deposition on a competent sediment surface from direct releases to surface water, with potential burial by sediment deposition (applies to DNAPL only), and

*(c)* Formation and deposition of OPAs, with potential burial by sediment deposition.

*(4)* Indicators for the potential presence and extent of NAPL, including observance of seeps, droplets and/or sheens within a water body.

*(5)* The potential for human and ecological exposures to NAPL in sediment or by means of NAPL release to overlying surface water.

4.6 The user of this guide should review the overall structure and components of this guide before proceeding with use, including:

4.6.1 Section 1 – Scope;

4.6.2 Section 2 – Referenced Documents;

4.6.3 Section 3 – Terminology;

4.6.4 Section 4 – Significance and Use;

4.6.5 Section 5 – Unique Aspects of Sediment Sites;

4.6.6 Section 6 – NAPL Emplacement Mechanisms;

4.6.7 Section 7 – NAPL Movement Decision Analysis Framework;

4.6.8 Section 8 – Keywords;

4.6.9 Appendix X1 – Emplacement Models: Potential NAPL Interactions at Surface Water Boundaries and Effects on NAPL Movement;

4.6.10 Appendix X2 – Sedimentary Processes and Groundwater – Surface Water Interactions;

4.6.11 Appendix X3 – NAPL Movement Terminology.

4.7 This guide provides an overview of the unique characteristics influencing the presence and potential movement of NAPL in aquatic sediment environments. This guide is not intended to provide specific guidance on sediment site investigation, risk assessment, monitoring or remedial action.

4.7.1 This guide may be used by various parties involved in a sediment site, including regulatory agencies, project sponsors, environmental consultants, site remediation professionals, environmental contractors, analytical testing laboratories, data reviewers and users, and other stakeholders.

4.7.2 This guide does not replace the need for engaging competent persons to evaluate NAPL emplacement and movement in sediments. Activities necessary to develop a CSM should be conducted by persons familiar with NAPL impacted sediment site characterization techniques, physical and chemical properties of NAPL in sediments, fate and transport processes, remediation technologies, and sediment evaluation protocols. The users of this guide should consider assembling a team of experienced project professionals with appropriate expertise to scope, plan, and execute sediment NAPL data acquisition activities.



## 5. Unique Aspects of Sediment Sites

5.1 This section discusses unique aspects of sediment sites for evaluating NAPL emplacement and NAPL movement in sediment, compared to evaluating NAPL emplacement and movement in upland soil. For the purposes of this section, sediment is considered a saturated material that is below a surface water body and soil is considered a saturated and unsaturated material below a ground surface.

5.2 NAPL may be emplaced within sediments through a variety of processes, including advection and deposition. These mechanisms and their effect on NAPL movement are described in Section 6. In contrast, the primary mechanism of NAPL emplacement in soil is advection.

5.2.1 The distribution of NAPL within sediment pores varies based on the processes of emplacement. Depending on the emplacement mechanism, NAPL may preferentially occupy either the larger pores or the smaller pores in sediment. In contrast, since NAPL emplacement in upland soil tends to be through one mechanism (advection), the general distribution of NAPL within soil pores tends to be similar from site to site – that is, NAPL in upland soil typically occupies the larger pores. Differences in the NAPL distribution within the sediment pore network and stratigraphic sequence affect the potential movement of NAPL.

5.3 The key differences in NAPL movement in sediment compared to soil are summarized below.

5.3.1 Vertical hydraulic gradients and upward NAPL migration to the sediment surface and the surface water are typically of primary interest for NAPL movement evaluations in sediment. Conversely, horizontal gradients and lateral NAPL migration are often the primary focus of NAPL movement assessments in soil.

5.3.2 In sediment, there is often a short vertical distance between the NAPL and potential receptors. In soil, the vertical distance between the NAPL and receptors is typically much greater.

5.3.3 Sediment lithology tends to vary more vertically than horizontally over the same distance. As a result, upward NAPL migration may encounter multiple lithologic layers with significant differences in pore size and pore entry pressure. In contrast, horizontal NAPL migration may encounter similar lithology with less variability in pore size and pore entry pressure. As vertical NAPL movement is of primary interest in sediment, there tends to be more vertical variability in lithology, pore size, and pore entry pressure in sediment compared to a similar horizontal distance in soil.

5.3.4 Surface water elevations may fluctuate more frequently than groundwater elevations. Some common causes of fluctuating surface water elevations are tides, precipitation, and anthropogenically controlled water elevation (for example, dams). Fluctuating surface water elevations can produce varying hydraulic gradients in strength and direction. The fluctuating hydraulic gradient may affect NAPL movement in sediment. In contrast, groundwater elevations typically fluctuate more slowly than surface water elevations do, resulting in less variability in NAPL movement in soil.

5.3.5 Sediments typically have higher porosity than soil. With higher porosity, a given volume of NAPL in sediment pore spaces has a lower NAPL saturation and may have less continuity and mobility. In contrast, the same volume of NAPL in lower porosity soil would have a higher NAPL saturation and possibly higher mobility.

5.3.6 Surface water bodies may have more sources of NAPL than upland sites. Each type of NAPL has unique physical properties that affect NAPL movement. Thus, sediment may have more variability in NAPL physical properties and potential for NAPL movement than soil.

5.3.7 Surface water bodies can be dynamic environments with erosion and deposition. Combined with the focus on vertical NAPL migration, as described in 5.2.1, these processes can affect NAPL movement. For example, erosion may expose sediments containing NAPL, enabling NAPL migration into the surface water. Conversely, surface sediment containing NAPL may be buried under depositing sediment, eliminating a potential NAPL migration pathway. In contrast, soil tends to be a more static system, with negligible erosion or deposition.

5.3.8 NAPL emplacement and movement mechanisms in sediment may differ significantly from upland sites. These concepts are discussed in greater detail in the following sections and Appendix X1.

## 6. NAPL Emplacement Mechanisms

6.1 *Considerations for Developing NAPL Emplacement Conceptual Site Models:*

6.1.1 *Site Conditions*—Many physical and chemical conditions influence the potential for NAPL movement. These conditions may be spatially variable and temporally limited. The relative importance of each site condition is site dependent. As such, characterization programs should consider each condition to determine their relative importance to NAPL movement. These components are briefly described below, and their significance with respect to NAPL emplacement is outlined in Tables 1-4.

6.1.1.1 *Bathymetry / Topography*—The bathymetry influences the movement of DNAPL along the sediment-water interface. After accumulating at the sediment interface, the



**TABLE 1 NAPL Emplacement Conceptual Model Components**

| CONCEPTUAL MODEL COMPONENTS | ADVECTIVE EMPLACEMENT | OPA DEPOSITION / IDN SEDIMENT | SURFACE FLOW ON SEDIMENT SURFACE |
|---|---|---|---|
| **Site Conditions** | | | |
| Bathymetry / Topography | ... | ... | X |
| Energy of the Environment (erosion, deposition, settings) | ... | X | X |
| Saline / Fresh Water Quality | ... | X | ... |
| Groundwater Elevation | X | ... | ... |
| Surface Water Elevation | X | ... | ... |
| Tidal Conditions | X | ... | ... |
| **NAPL Conditions** | | | |
| Source of NAPL | X | X | X |
| NAPL Source History | X | X | X |
| NAPL Distribution Relative to Source | X | X | X |
| NAPL Lateral Distribution in Sediments | X | X | X |
| NAPL Vertical Distribution / Depth in Sediments | X | X | X |
| NAPL Physical Properties (density, viscosity, etc.) | X | X | X |
| **Sediment Conditions** | | | |
| Sediment Texture / Particle Size | X | X | X |
| Sediment Hydraulic Conductivity | X | ... | ... |
| Sediment Stratigraphy | X | X | X |
| NAPL-Stratigraphic Correlation | X | X | X |

"..." = Not Applicable to emplacement conceptual model

**TABLE 2 NAPL Emplacement Conditions: Advective Emplacement**

| | ADVECTIVE EMPLACEMENT |
|---|---|
| **Site Conditions** | |
| Bathymetry / Topography | ... |
| Energy of the Environment (erosion, deposition, settings) | ... |
| Saline / Fresh Water Quality | ... |
| Groundwater Elevation | Location of LNAPL |
| Surface Water Elevation | Location of Potential Seep |
| Tidal Conditions | Thickness of Smear Zone |
| **NAPL Conditions** | |
| Source of NAPL | LNAPL / DNAPL Source |
| NAPL Source History | Active or Terminated |
| NAPL Distribution Relative to Source | Connected to Source |
| NAPL Lateral Distribution in Sediments | Proximal to Shoreline |
| NAPL Vertical Distribution / Depth in Sediments | At Depth - Upward Movement |
| NAPL Physical Properties | Controls Emplacement / Velocity |
| **Sediment Conditions** | |
| Sediment Texture / Particle Size | Important to Migration Potential |
| Sediment Hydraulic Conductivity | Important to Migration Potential |
| Sediment Stratigraphy | NAPL Emplaced after Strata |
| NAPL-Stratigraphic Correlation | Potentially Cutting Across Strata |

"..." = Not Applicable to emplacement conceptual model

**TABLE 3 NAPL Emplacement Conditions: OPA Deposition and IDN Sediment Formation**

| | OPA DEPOSITION / IDN SEDIMENT |
|---|---|
| **Site Conditions** | |
| Bathymetry / Topography | ... |
| Energy of the Environment (erosion, deposition, settings) | Deposition Required |
| Saline / Fresh Water Quality | Influences OPA Formation |
| Groundwater Elevation | ... |
| Surface Water Elevation | ... |
| Tidal Conditions | ... |
| **NAPL Conditions** | |
| Source of NAPL | LNAPL Source |
| NAPL Source History | Active or Terminated |
| NAPL Distribution Relative to Source | Disconnected |
| NAPL Lateral Distribution in Sediments | Potentially Large Footprint |
| NAPL Vertical Distribution / Depth in Sediments | Generally thin, shallow depths |
| NAPL Physical Properties | <1.0 g/cm$^3$ |
| **Sediment Conditions** | |
| Sediment Texture / Particle Size | Effects Encapsulation |
| Sediment Hydraulic Conductivity | ... |
| Sediment Stratigraphy | NAPL Emplaced with Strata |
| NAPL-Stratigraphic Correlation | Coincident with Strata |

"..."= Not Applicable to emplacement conceptual model



DNAPL body will flow due to gravity along the interface toward areas of low elevation.

6.1.1.2 *Energy of the Environment (Erosional/Depositional Setting)*—The environmental setting affects the potential preservation of deposited NAPL. IDN sediments and DNAPL bodies at the sediment surface will be potentially eroded and scoured in water bodies characterized by high flow velocities. As such, the presence of depositionally-emplaced NAPL zones typically reflect low energy, depositional settings.

6.1.1.3 *Saline/Fresh Water Quality*—Salinity may affect the interfacial tension (IFT) between the aqueous and NAPL phases. Typically, higher salinity will lower IFT and increase the potential for wettability of the NAPL phase. Increasing the wettability increases the potential for NAPL movement. IFT also influences the size of oil droplets that can be generated during the formation of an OPA.

6.1.1.4 *Groundwater Elevation*—The elevation of the groundwater primarily influences LNAPL advective emplacement, since LNAPLs typically migrate at the groundwater table. When the elevation of the sediment surface is above the groundwater table, such as might occur in a depositional setting (that is, point bars), then LNAPL migration may impact these sediments. Where the groundwater elevation occurs above a sediment deposit, LNAPL will discharge directly to the surface water to form a sheen and the sediment will not be directly affected.

6.1.1.5 *Surface Water Elevation*—The elevation of the surface water influences the gradient and potential fluctuations in the groundwater. As a result, LNAPL movement into the sediment is influenced by the interaction of the surface water and groundwater. A NAPL smear zone will result in proximity to the seepage face from LNAPL oscillations that result from dynamic surface water fluctuations.

6.1.1.6 *Tidal Conditions*—Dynamic fluctuating water elevations produce oscillating hydraulic gradients and pressures that influence advective NAPL flow. These changing pressure

TABLE 4 NAPL Emplacement Conditions: Surface Flow on Sediment Surface

| | SURFACE FLOW on SEDIMENT SURFACE |
|---|---|
| **Site Conditions** | |
| Bathymetry / Topography | Controls Gradient |
| Erosional / Depositional Setting | Controls Exposure |
| Saline / Fresh Water Quality | ... |
| Groundwater Elevation | ... |
| Surface Water Elevation | ... |
| Tidal Conditions | ... |
| **NAPL Conditions** | |
| Source of NAPL | DNAPL Source |
| NAPL Source History | Active or Terminated |
| NAPL Distribution Relative to Source | Connected to Discharge Location |
| NAPL Lateral Distribution in Sediments | Proximal to Shoreline |
| NAPL Vertical Distribution / Depth in Sediments | At Sediment Interface / Shallow Depth |
| NAPL Physical Properties | >1.0 g/cm$^3$ / viscosity effects migration |
| **Sediment Conditions** | |
| Sediment Texture / Particle Size | Particles Incorporated into DNAPL |
| Sediment Hydraulic Conductivity | ... |
| Sediment Stratigraphy | NAPL Emplaced with Strata |
| NAPL-Stratigraphic Correlation | Coincident with Strata |

"..." = Not Applicable to emplacement conceptual model

conditions may act to reverse hydraulic and/or the NAPL gradients both laterally and vertically.

6.1.2 *NAPL Conditions:*

6.1.2.1 *Source of NAPL*—The source of the NAPL affects all forms of emplacement. How, when, and where the NAPL was emplaced are important components to determine, if possible. The source of the NAPL can be quite variable, ranging from pipe and tank releases occurring at an upgradient facility, to direct spills or discharges into the open water body. The source of NAPL directly affects such emplacement factors as the type, location, and extent of the NAPL zone.

6.1.2.2 *NAPL Source History*—Understanding the NAPL source history is important in evaluating the distribution, area of impact, and longevity of the NAPL movement. Common issues to resolve, if possible, are how long was the source active, what was the volume and rate of release(s), and when did the source end (or is it ongoing). The aspects of the NAPL source history directly affect such emplacement factors as the type, location, and extent of the NAPL zone.

6.1.2.3 *NAPL Distribution Relative to Source*—The spatial distribution of the NAPL zone relative to the source is an important factor in evaluating the emplacement process. Typically, advective and DNAPL surface flow emplacements are directly connected to the source. However, IDN sediments resulting from the transport of OPAs within the water column may be physically separated (sometimes by large distances) from the source.

6.1.2.4 *NAPL Lateral Distribution in Sediments*—Determining the lateral extent of the NAPL zone aids in defining the emplacement mechanism. Advective emplacement is commonly located near the upland and is localized to areas near the shoreline of the upland source zone. In contrast, an IDN NAPL zone may be widespread and extend over many hectares.

6.1.2.5 *NAPL Vertical Distribution / Depth in Sediment*—Depositionally-emplaced NAPL bodies form at the sediment-water interface and, hence, will be correlative with the surrounding strata. In contrast, advectively-emplaced NAPL occurs at depth within the sediment, commonly due to vertical gradient flow across different layers of strata.

6.1.2.6 *NAPL Physical Properties*—Density, viscosity, and interfacial tension are critical properties that influence NAPL emplacement and movement. The density of a NAPL (LNAPL versus DNAPL) produces different forms of emplacement (that is, OPA formation versus DNAPL flow at the sediment surface). NAPL viscosity influences the movement of NAPL, both advective and sediment surface flow. Interfacial tension may influence advective wettability, as well as the size of oil droplets in the formation of an OPA.

6.1.3 *Sediment Conditions:*

6.1.3.1 *Sediment Texture / Particle Size*—The size of solid particles affects many aspects of NAPL emplacement. Advective movement is controlled by the pore size of the sediment, which is directly related to grain size. The larger the pore size (that is, the larger the particle size) the greater the potential for NAPL movement, since lower pore entry pressures are required to evacuate the water-filled void spaces within the sediment. Particle size also influences the degree of encapsulation in OPA formation. In general, the smaller the particle size the greater the degree of encapsulation.

6.1.3.2 *Sediment Hydraulic Conductivity*—The hydraulic conductivity influences advective NAPL emplacement. Typically, NAPL will migrate along the path of least resistance (the highest hydraulic conductivity pathways). In contrast, the occurrence of NAPL within fine grain sediments is not generally consistent with advection and may be reflective of other emplacement mechanisms (for example, IDN emplacement).

6.1.3.3 *Sediment Stratigraphy*—Determining the sediment stratigraphy provides information on the thickness of the strata, the location of contacts, and the stratigraphic layers that are conducive to NAPL movement. The energy of deposition and its temporal variability is recorded in the stratigraphic sequence, so this component is particularly important in evaluating the emplacement mechanism for depositionally-emplaced NAPL. Advectively-emplaced NAPL zones are not affected by the depositional environment and are located at depth below the sediment-water interface. Additional discussion of sedimentary processes and their effect on sediment stratigraphy is provided in Appendix X2.

6.1.3.4 *NAPL-Stratigraphic Correlation*—Correlating the spatial distribution of the NAPL zone with the stratigraphy provides useful information of the emplacement process. The occurrence of depositionally-emplaced NAPL will be correlative to the strata, while the occurrence of advectively-emplaced NAPL will commonly not be correlative to the strata.

6.2 *Physical Processes of NAPL Emplacement:*

6.2.1 There are two primary physical processes that emplace NAPL within sediments: *(1)* advective flow, and *(2)* deposition through the water column (includes both sediment surface flow of DNAPL and formation of IDN sediments from LNAPL). A detailed discussion of emplacement conceptual models is included in Appendix X1, while a more detailed discussion of interactions between groundwater and surface water is included in Appendix X2.

6.2.2 The advective flow of NAPL occurs when a continuous phase of NAPL derived from an upland source has sufficient volume and pore entry pressure to enter the sediment. In advective flow, the NAPL pressure exceeds the pore entry pressure of the sediment matrix and displaces the porewater. Advective emplacement occurs after sediment formation within the existing sediment pore structure. The distribution of NAPL may be highly variable depending on hydraulic conditions, as well as the NAPL volume and NAPL gradient induced by historical releases from upland sources. Example advective emplacement conceptual models are presented for LNAPL and DNAPL (Fig. 1).

6.2.3 In both depositional emplacement mechanisms (sediment surface flow of DNAPL and formation of IDN sediments from LNAPL), the relative density of the NAPL versus the aqueous phase has a large effect on the distribution of the NAPL in the surface water body and associated sediments. In contrast to advective emplacement, depositional emplacement of NAPL occurs during sediment formation and the NAPL is incorporated as part of the sediment matrix. The distribution of NAPL from depositional emplacement is largely influenced by the varying densities of the NAPL.

6.2.4 For an LNAPL to become deposited within the sediment, the LNAPL, which forms a layer at the water surface, must be physically separated into distinct oil beads or droplets and dispersed through the water column. Here, solid particles adhere to the LNAPL beads (Fitzpatrick et al., 2015 (**1**))[3]. As particles adhere to the oil bead, the density of the aggregate (that is, oil and particles) eventually exceeds the density of the aqueous phase. These oil-particle aggregates (OPAs) then fall through the water column and become deposited with the sediment. The resulting OPA-containing sediment are termed *In situ* Deposited NAPL (IDN) sediments (Johnson et al., 2018a (**2**)). In contrast, a DNAPL entering a surface water body (for example, discharge from a pipe) will sink directly through the water column and form a layer at the sediment surface. The DNAPL may flow along the sediment interface (due to gravitational forces) forming a DNAPL body directly on the sediment surface. Examples of NAPL emplacement with respect to the relative density of the NAPL are illustrated in Fig. 1.

6.2.5 The components requiring evaluation in developing NAPL emplacement conceptual models are presented in Table

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.



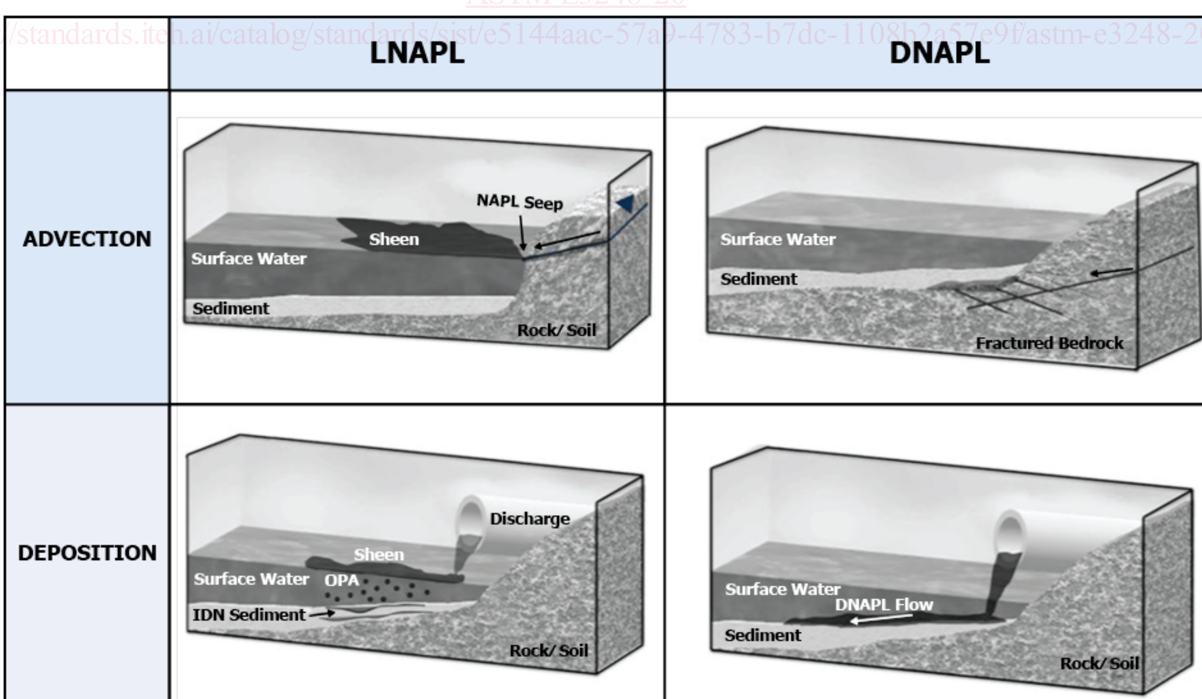



**FIG. 1 Example NAPL Emplacement Conceptual Models**

1. How emplacement affects NAPL movement is discussed in detail in 6.3 and 6.4, as well as Appendix X1.

6.3 *Advective NAPL Emplacement:*

6.3.1 Advective NAPL emplacement results from the movement of a NAPL plume from an upland source to the sediment and/or surface water body. This emplacement produces a continuous phase of NAPL within the largest pores of the sediment matrix. The character of the NAPL distribution is dependent upon many factors, including:

- The NAPL pressure at the time of emplacement;
- The pore size distribution of the sediment;
- The density of the NAPL;
- The geologic conditions between the upland source and the surface water body;
- The interfacial tension conditions between the sediment, water and NAPL; and
- The hydrodynamics of the surface water body.

6.3.2 In general, advectively-emplaced NAPL will be observed in coarser sediments, such as sands and gravelly sands, as these are more permeable and have generally lower pore entry pressures than finer grain sediments. The area of sediment impacted by NAPL occurs proximal to the groundwater-surface water boundary and is generally localized to areas near the shoreline of the water body. The sediment impacts are directly connected to an upland source.

6.3.3 Advective NAPL emplacement may produce conditions conducive to NAPL movement. Critical elements associated with advectively-emplaced NAPL that require defining in the conceptual site model include the physical properties of the NAPL and sediment, an assessment of the NAPL source, and surface-groundwater interactions (Table 2).



6.4 *OPA Deposition Forming IDN Sediments:*

6.4.1 The IDN sediment bed results from the formation of OPAs from LNAPL beads and suspended particulates, followed by deposition of the OPAs through the water column onto the sediment bed over long periods of time. Although IDN sediments can range in particle size from clays to sands, finer grained IDNs are more widespread, since these can remain suspended within the water column over larger areas (for example, many hectares). The thickness of the IDN sediment is controlled by the nature and longevity of the LNAPL discharge, the concentration and particle size distribution of suspended particles in the water column, and the energetics of the depositional environment. The IDN sediment resulting from the OPA deposition consists of a collection of discrete OPAs that form a network of small pores, where oil is either fully or partially encapsulated by solid particles (Johnson et al., 2018b (**3**)). Results of capillary pressure testing and electron microscopy suggest the OPA structure is retained upon deposition.

6.4.2 All things being equal, due to the structure of the OPA, LNAPL within IDN sediments will be less mobile than when LNAPL is emplaced advectively. In IDN sediments, the LNAPL occurs in the smaller openings of the sediment matrix and may be totally encapsulated by solid particles. For totally encapsulated LNAPL, the original OPA structure generally inhibits the oil beads from coalescing, which limits the potential for NAPL mobility. Partially encapsulated LNAPL will have a higher potential for mobility than fully encapsulated LNAPL. Critical elements to be addressed in developing the conceptual model for IDN sediments are listed in Table 3. These include the NAPL distribution in the sediment, the sediment stratigraphy, and the energy of deposition.

6.5 *NAPL Surface Flow:*

6.5.1 NAPL surface flow is produced when a DNAPL is discharged into a surface water body and accumulates on a competent sediment bed. It is important to note that the competent sediment surface may lie below a layer of unconsolidated, "fluffy" sediment. As the DNAPL body flows across the sediment surface, particles become entrained within the DNAPL matrix. The resulting deposit consists of DNAPL, with some sediment particles. There is a distinct boundary between the sediment and the DNAPL body. The flow of the DNAPL will extend from the point of discharge, following the slope of the sediment surface. The flow of DNAPL will stop when it pools, there is no slope and/or the DNAPL source is depleted. The resultant DNAPL may become covered in locations where deposition is occurring; but may also be eroded in higher energy environments, since the DNAPL occurs directly on the sediment surface.

6.5.2 Surface flow DNAPL emplacement may produce conditions conducive to DNAPL movement. Important components of the emplacement conceptual model for DNAPL surface flow sites include the physical properties of the NAPL, the conditions associated with the source and discharge, and the orientation of the sediment surface (Table 4).

6.6 *Movement of Emplaced NAPL In Sediment by Advection:*

6.6.1 In this guide, the term "advection" refers to the bulk flow of NAPL through pore spaces within sediment. For NAPL to be capable of advection, it must be present as a continuous fluid phase, connected through the pore spaces between solid particles. Also, for NAPL to move into pore spaces where there is currently no NAPL, the NAPL must overcome the pore entry pressure of the sediment matrix; this process depends on the sediment physical characteristics, capillary pressure, NAPL-water interfacial tension, and the surface interactions between NAPL, water and sediment (wettability). The rate of NAPL advection, if any, depends on the sediment characteristics, hydraulic gradient, density-driven gradient, pore fluid saturation, NAPL viscosity, and relative permeability. NAPL advection can be quantified by collecting and using these types of site-specific data.

## 7. NAPL Movement Decision Analysis Framework

7.1 *Need for a NAPL Emplacement and Movement Evaluation:*

7.1.1 Characterizing NAPL movement is not necessary at all contaminated sediment sites. The obvious case where NAPL movement is not a concern is at sites (or portions of larger sites) where NAPL has not been observed during field screening and/or identified based on laboratory analysis of sediment samples. Even in cases where NAPL presence is confirmed in sediments, the emplacement conditions largely control NAPL movement. As such, determining the operable emplacement process is an important component of a sound conceptual site model in assessing the movement of the NAPL phase. Since laboratory NAPL mobility analyses require specialized sample collection and handling procedures, which can be expensive and time consuming, it is important that such an evaluation only be performed if warranted. Fig. 2 is a flow chart that provides a technical framework to determine if a NAPL emplacement and movement evaluation is warranted at a sediment site.

7.1.2 The initial step in a NAPL emplacement and movement evaluation is to determine whether or not NAPL is known or suspected to be present. A study of potential current and historic NAPL sources may aid in identifying suspect locations and emplacement mechanisms. Current and/or historical observations of NAPL releases or sheens at the site may indicate NAPL presence. However, at most sites the presence or absence of NAPL in sediment must be confirmed by collecting sediment samples and performing field screening on these samples.

7.1.3 If field screening indicates that NAPL is not present in the sediment, then a NAPL emplacement and movement evaluation is not warranted. However, if NAPL presence is confirmed, the next step is to delineate the extent of the NAPL zone. After the NAPL zone has been delineated, at some sites the decision may be made to remove the NAPL impacted sediments (for example, by means of dredging) – this option may be the selected if the NAPL zone is small and easy to

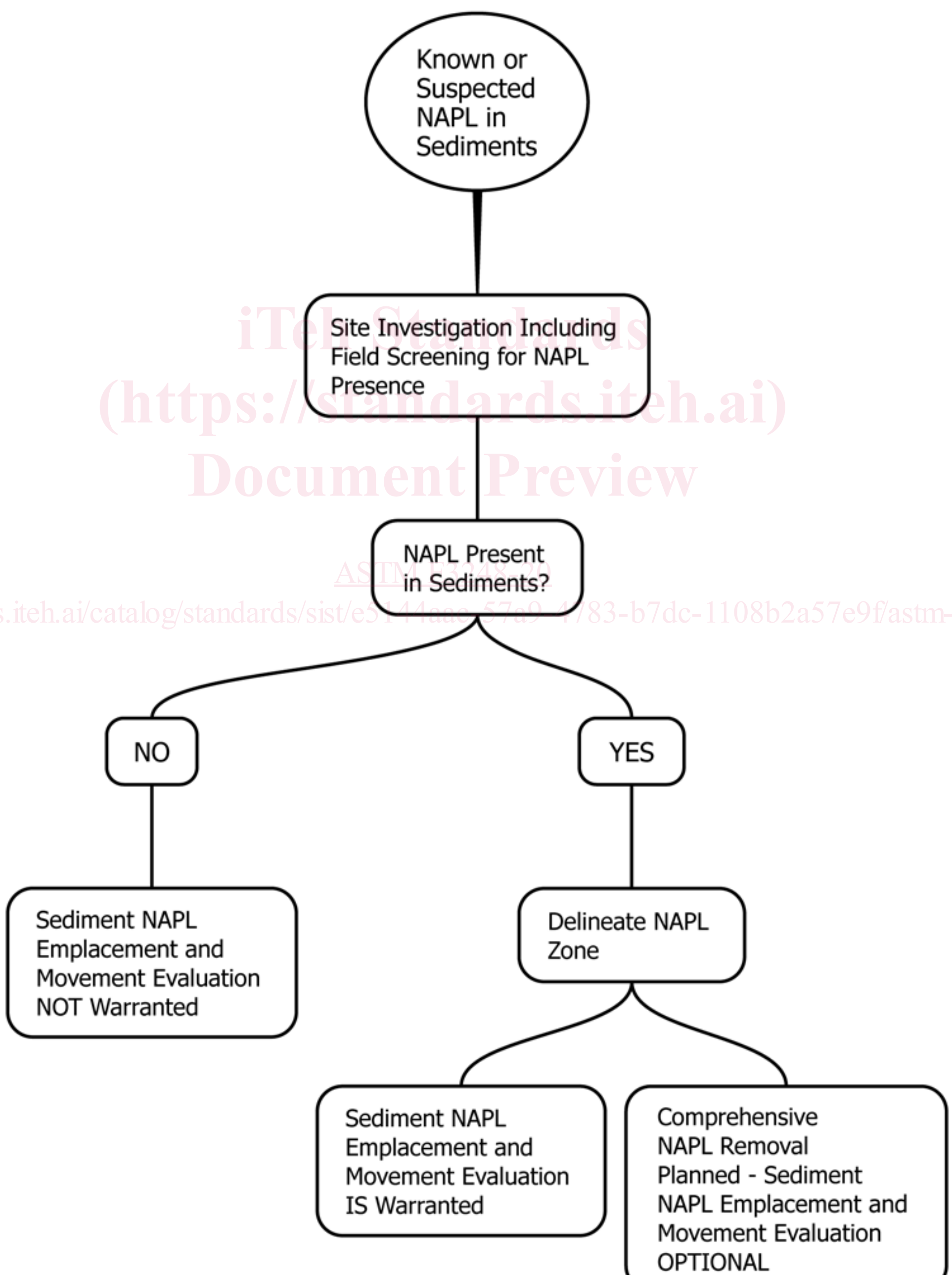



**FIG. 2 Process to Determine the Need for a NAPL Emplacement and Movement Evaluation**

access for removal activities. If comprehensive removal of the NAPL impacted sediment is the planned remedial option, then a NAPL emplacement and movement evaluation before the remedy would be optional. Otherwise, a sediment NAPL emplacement and movement evaluation is warranted.

7.2 *NAPL Movement Evaluation Framework:*

7.2.1 After the decision has been made to perform a NAPL movement evaluation at a contaminated sediment site (or in a portion of that site), the evaluation should consider assessment of NAPL movement at both the pore (that is, void) and NAPL body scales (Fig. 3). Appendix X3 provides further information on the movement of NAPL at the pore and NAPL body scales.

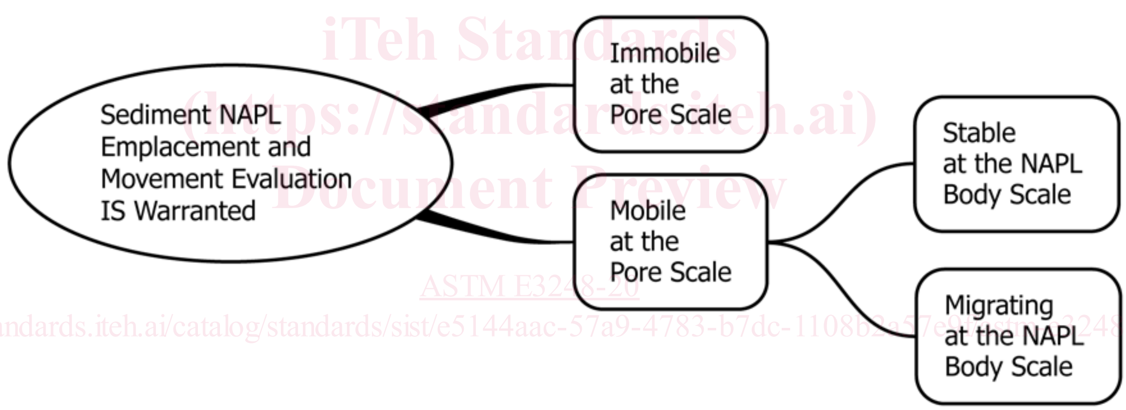
7.2.2 Typically, NAPL movement by means of advection is first evaluated at the pore scale. Evaluating NAPL mobility at the pore scale requires collecting minimally-disturbed sediment samples and performing laboratory tests. If NAPL is determined to be immobile at the pore scale, then no further NAPL movement evaluation is required, because NAPL that is not advectively moving at the pore scale cannot be migrating at the NAPL body scale (that is, the NAPL must be stable at this scale). If NAPL is determined to be mobile at the pore scale, then the evaluation must be continued to determine if the NAPL body is stable or migrating.

7.2.2.1 Pore scale mobility evaluations are generally conducted through laboratory testing. Laboratory NAPL mobility tests can be performed under a variety of applied stresses in an attempt to mobilize NAPL from the sediment. The applied hydraulic pressures during pore scale laboratory NAPL mobility testing should be equal to, or more conservative than (that is, greater than) those observed and/or reasonably anticipated in the field under natural conditions.

7.2.3 NAPL body scale migration evaluations consider *in situ* field conditions (that is, NAPL presence/absence; stratigraphic conditions; calculation of horizontal and vertical gradients; and sediment physical property measurements). If mathematical analysis is conducted, then some model parameter values can be supported from the results of the pore scale mobility tests and/or from additional laboratory analyses (for example, NAPL fluid properties such as density, viscosity and interfacial tension; pore entry pressures).

## 8. Keywords

8.1 *in situ* deposited NAPL (IDN); NAPL; NAPL advection; NAPL body; NAPL movement; oil-particle aggregate (OPA)






NOTE: Each line indicates an evaluation is performed.

**FIG. 3 NAPL Movement Evaluation Framework**