

# Soil Properties and Design Factors Influencing Free-Phase Hydrocarbon Cleanup

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Light nonaqueous phase liquid (LNAPL) saturation and movement in the subsurface are controlled by soil capillary characteristics, permeability, and fluid properties. Where free-product occurs in monitoring wells, LNAPL saturations in the formation vary significantly as a function of the observed thickness in the monitoring well and soil type. Fine-grained soils generally exhibit lower LNAPL saturations than coarse-grained material for the same observed thickness in a monitoring well. MAGNAS3 [MAGNAS3. HydroGeoLogic, Inc., Herndon, VA, 1992; Huyakorn, P. S.; Panday, S.; Wu, Y. S. *J. Contam. Hydrol.* **1994**, *76*, 190–130], a three-dimensional, finite-element model that can simulate movement of three active phases (air, water, and LNAPL), was used to investigate LNAPL recovery in three different soil types and using several recovery designs to examine the effect of these factors on LNAPL recovery. The results of this analysis show that, because the relative mobility of LNAPL decreases with decreasing saturation and because the intrinsic permeability of fine-grained soil is less than that of coarse-grained soil, free-product pumping or skimming has less likelihood of success in fine-grained soil. Recovery in fine-grained soils was minimal, with significant reductions in LNAPL saturation occurring only within about 10–15 ft of the well. Recovery of LNAPL in coarse-grained soils was simulated to be much more successful, with approximately 95% of the original hydrocarbon recovered through fluid pumping. The results of the modeling further shows that, for any soil type, recovery decreases LNAPL saturation and mobility near the well with the effect diminishing with distance. Therefore, a zone of decreased LNAPL permeability is formed near recovery wells that acts to impede additional recovery from greater distances. Increases in the hydraulic recovery rate (i.e., not considering volatilization) can be realized in all of the soils studied through vacuum enhanced free-product recovery.

## Introduction

Light nonaqueous phase liquids (LNAPL), such as gasoline, fuel oil, and a host of other products, are sometimes released to the subsurface. Many contain compounds that can adversely affect human and environmental health. Therefore,

it has been the general practice of health regulators to require the cleanup of free-phase LNAPL at sites where it has been observed in monitoring wells. However, free-product recovery by fluid pumping (skimming and groundwater withdrawal) has had limited success at completely remediating sites. For instance, in downtown San Diego, an LNAPL pool known as the “blob” displays hydrocarbon thicknesses in observation wells up to 10 ft. The plume is estimated to have an approximate volume of 64 000 gal (4). However, free-product pumping has resulted in only limited recovery, with less than 1000 gal collected over 3 years by the pilot cleanup system.

There are several reasons for these field observations. First, even if an appreciable thickness of free product is present in an observation well, the LNAPL saturations in soil (percent of pore space occupied by LNAPL) may be small, resulting in limited LNAPL mobility and recovery. Second, as skimming and pumping proceeds, the area near the recovery well experiences the greatest reduction in hydrocarbon saturation. This leads to a reduction in the relative permeability toward LNAPL in that region, effectively forming a zone that inhibits hydrocarbon recovery from greater distances. Lastly, some LNAPL recovery systems are poorly optimized. LNAPL movement and recovery are strongly soil type dependent. The mechanics of some skimming and pumping systems do not allow the control necessary for optimum free-product recovery.

The objectives of this study are to (1) quantify how soil type affects hydrocarbon recovery rate and ultimate effectiveness; (2) enumerate the physical limitations to LNAPL recovery; and (3) quantify the effects of applying a vacuum to the LNAPL recovery system, ignoring volatilization. Considerations of other LNAPL mass removal mechanisms, such as mass partitioning and biodegradation, are not within the scope of this study. However, as will be apparent at the conclusion of this paper, other mass removal mechanisms will exceed LNAPL hydraulic recovery at some point in time for most soils.

## Multiphase Dynamics Overview

Petroleum engineers have long been aware that it is more difficult to remove oil (LNAPL) from reservoirs in the presence of water. Until recently, this was not generally considered relevant in contaminant hydrology because LNAPL was thought to float as a distinct layer on the capillary fringe (5) and flow into an observation well by gravity drainage, “exaggerating” the formation thickness. Field and laboratory data have shown this conceptual model to be incorrect, primarily because it does not account for groundwater pore displacement caused by the weight of LNAPL. Rather, under vertical equilibrium, multiphase fluid theory suggests that hydrocarbon and water coexist in soil pores throughout the measured thickness interval in a monitoring well (6, 7) (Figure 1, panels a and b). The relative pore saturation of water, LNAPL, and air in the formation depend on fluid properties and soil capillary characteristics and, under vertical equilibrium conditions, can be estimated from the associated monitoring well LNAPL thickness measurements. Field comparisons between predicted and measured hydrocarbon saturations and mobility (8, 9) are consistent with multiphase fluid theory. This is not surprising since multiphase theory has been used for decades to reliably represent flow and recovery in petroleum reservoirs containing brine water, oil, and vapor.

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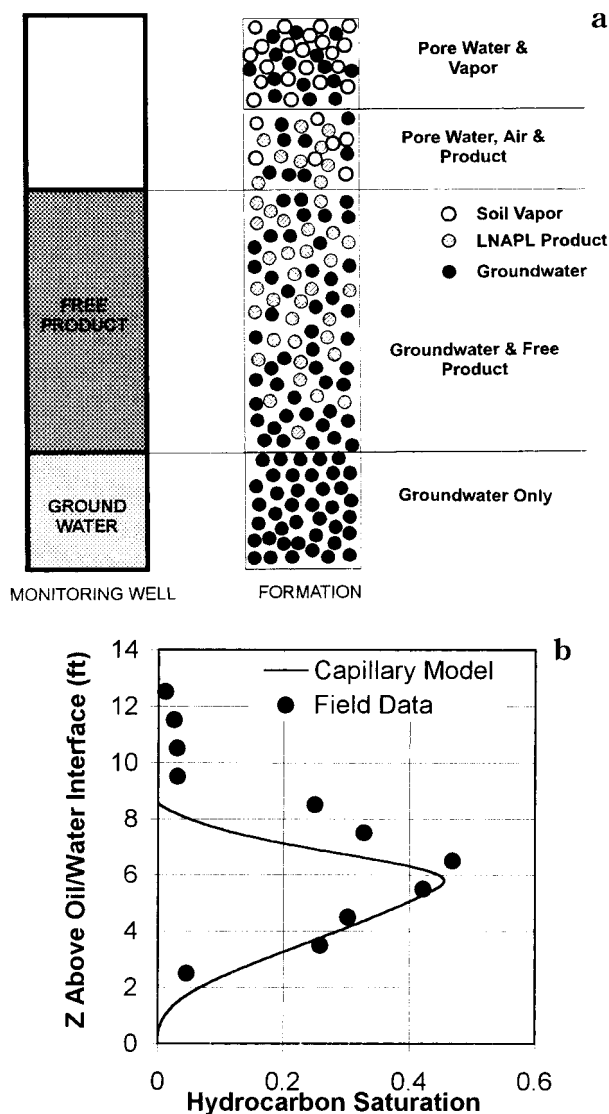


FIGURE 1. (a) Schematic relationship between observed well LNAPL thickness and formation saturation (after ref 6). (b) Measured versus calculated LNAPL saturation for a fine sand having about 8 ft of observed thickness.

Multiphase theory indicates that the idea of an exaggerated thickness of LNAPL is erroneous. If the system is in vertical equilibrium, the LNAPL thickness observed in a monitoring well is less than the thickness of soil affected by the free product (because an oil/water/air capillary fringe is also present). This vertical equilibrium thickness does not include any over- or underlying residual product stranded as a function of release history or groundwater level variations. However, because LNAPL and water coexist in the free-product zone (Figure 1, panels a and b), the volume of product in the interval is less than the maximum pore volume available. This effect is more significant as the grain size decreases. This can result in a *volume* exaggeration and set unrealistic precedents for site closure goals if the site scientist is unaware of how LNAPL is distributed within the formation.

The modeling in this study uses the code MAGNAS3, which is equivalent to an oil reservoir simulator extended to environmental release conditions. The solutions are based on Darcy's law for multiphase fluid flow and the linked mass conservation equation. For those interested, the pertinent equations and detailed model boundary conditions are included as an appendix in the Supporting Information. A simple form of Darcy's law (eq 1) shows the important

TABLE 1. Soil Parameters Used in Simulations

parameter	soil 1: ML	soil 2: SM	soil 3: SW
permeability ( $m^2$ )	1.78e-13	3.21e-13	1.54e-11
porosity	0.441	0.381	0.305
Van Genuchten $\alpha$ ( $m^{-1}$ )	0.67	0.9	7.34
Van Genuchten $n$	1.325	2.29	2.27
residual moisture (estd)	5.00e-03	5.00e-03	5.00e-03

concepts and parameters

$$q_p = K_{eff,p} i_p \quad (1)$$

where  $q_p$  is the specific discharge flow of phase  $p$ ,  $K_{eff}$  is the effective hydraulic conductivity toward any phase (water, LNAPL, air), and  $i_p$  is the net gradient of that phase. As mentioned previously, the effective conductivity depends on the fluid specific weight ( $\rho g$ , where  $\rho$  is the fluid density and  $g$  is the acceleration due to gravity) and ( $\mu$ ) viscosity, the intrinsic soil permeability at any point, and the relative permeability, which depends on pore fluid saturation (10) (i.e.,  $K_{eff} = k_r k_i (\rho g / \mu)$ ). Pore saturations of any fluid are controlled by the soil capillary properties (11) that, in turn, exert an exponential impact on the effective phase conductivity. As phase saturation decreases, so does the effective hydraulic conductivity toward that phase.

### Study Approach

Three soil types, typical of the categories ML, SM, and SW in the Unified Soil Classification System (USCS), were selected for study in context with LNAPL recovery. The USCS system is widely used by earth scientists and engineers to designate soil types. A specific soil representing each of these classes was selected from a catalog containing necessary physical information (12) (Table 1). Other fluid and physical parameters used in the simulations are provided in the Appendix in the Supporting Information. The ML selected was a silt loam that contained approximately 16% clay and 54% silt, with the remainder fine- to very-coarse-grained sand. The SM was a sand loam that contained approximately 9% clay and 26% silt, with the remainder fine- to very-coarse-grained sand. The SW was a clean, well-graded sand containing about 35% very-fine- to fine-grained sand and 65% medium- to very-coarse-grained sand. Since soil hydraulic properties can vary widely within any USCS designation, the results of this study are comparative. As will be seen later, the SW contrasted significantly with the SM and ML, but the SM and ML soils behaved similarly due to the presence of fine-grained materials in each. This indicates the difficulty in using the USCS to infer modeling parameters and suggests that site-specific parameters are required to evaluate LNAPL recovery schemes.

MAGNAS3 (1, 2, 3) was used to simulate the vertical and radial distribution of LNAPL in a radially symmetric domain for each of the test cases evaluated. It should be noted that hysteresis of the capillary characteristic curves was not taken into account in these simulations, which has the effect of assuming a residual LNAPL saturation of zero, although the code can account for an explicit residual saturation term. This effectively results in LNAPL recovery estimates that pertain to the mobile LNAPL fraction only. This has no significant effect on the fine-grained soils because mobility is limited by small effective conductivity terms, but overestimates the total volume recovered from the SW soil. The radial domain cross-dimensions were 15 by 57.5 m, with the original water table (before LNAPL loading) at approximately 10 m (Figure 2). The model grid was dimensioned to have high vertical and lateral resolution near the recovery well. The effect of groundwater production on water levels was

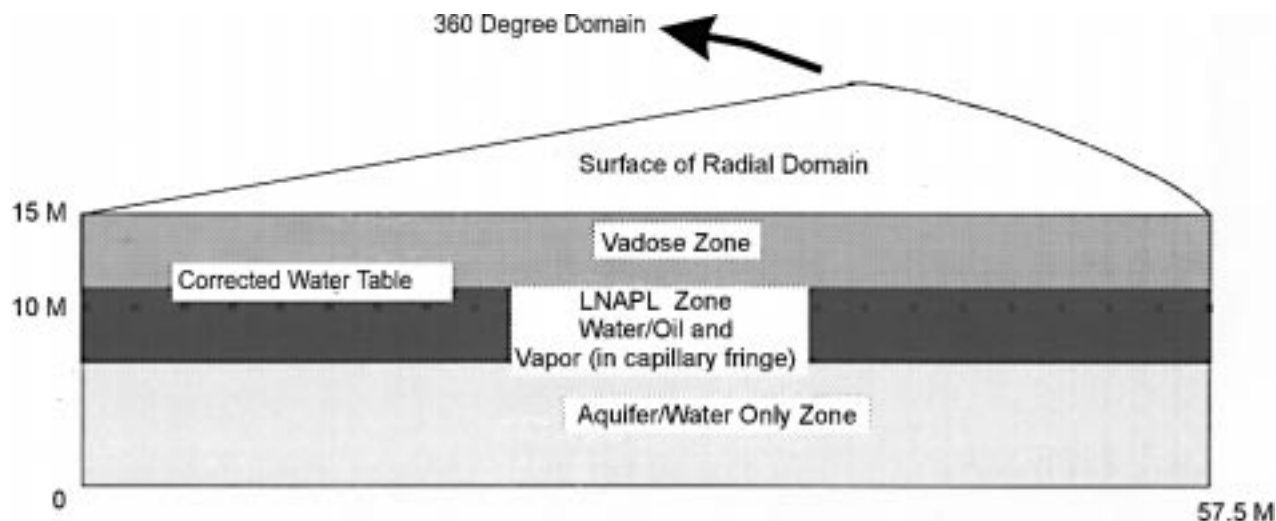


FIGURE 2. Schematic of radial model domain. Recovery well is in center of the domain; the corrected water table or piezometric surface is at 10 m, and the total model elevation is 15 m.

assumed to be limited to the modeled domain, and the initial LNAPL pool consisted of a finite volume and thickness of product evenly distributed according to the calculated saturation profile associated with a given well thickness, soil, and fluid properties. These conditions result in a constant head (i.e., no drawdown) condition with respect to water and a no-flow condition with respect to product at the distal model boundary. The LNAPL recovery well conditions were prescribed by selecting a drawdown and vacuum (as appropriate) within the well for each appropriate phase (water, LNAPL, air) resulting in conditions similar to those imposed by many commercially utilized cleanup systems. Additional model construction details are provided in the appendix in the Supporting Information.

Four sets of simulations were performed to evaluate various aspects of LNAPL recovery. The model domain was identical for each case, with soil, LNAPL volume, and recovery parameters varied to quantify their effects. The initial portion of the study evaluates fluid recovery (LNAPL and water) through time in three different homogeneous, isotropic soils using hydrocarbon skimming aided by groundwater pumping from the recovery well. For these cases, each soil was modeled to have an LNAPL saturation profile such that 3.05 m (10 ft) of free product would be observed in a monitoring well at equilibrium with the formation before pumping (Figure 3a).

For the first set of simulations, the boundary conditions at the well simulated the effect of a dual-phase pump placed at the original oil/water interface in the well, with water and LNAPL pumped at the maximum rate allowed by the formation. This resulted in a lowering of the groundwater piezometric surface by 2.3 m (7.5 ft) and the oil/air interface in the well by 3.05 m (10 ft).

The second set of simulations considered two different initial hydrocarbon distributions. The first simulation used initial hydrocarbon saturations corresponding to only 2 ft of hydrocarbon in a monitoring well, while the second assumed 5 ft of hydrocarbon in a monitoring well (Figure 3b). These simulations were both conducted only for the intermediate soil type (SM).

The third set of simulations evaluated the effect of varying groundwater and hydrocarbon pumping rates on total free product recovery, by varying drawdown in the production well. The last portion of the study considered the effect of an applied vacuum on LNAPL recovery. Field studies and experience have suggested that an applied vacuum increases free-product recovery. However, quantification of underlying

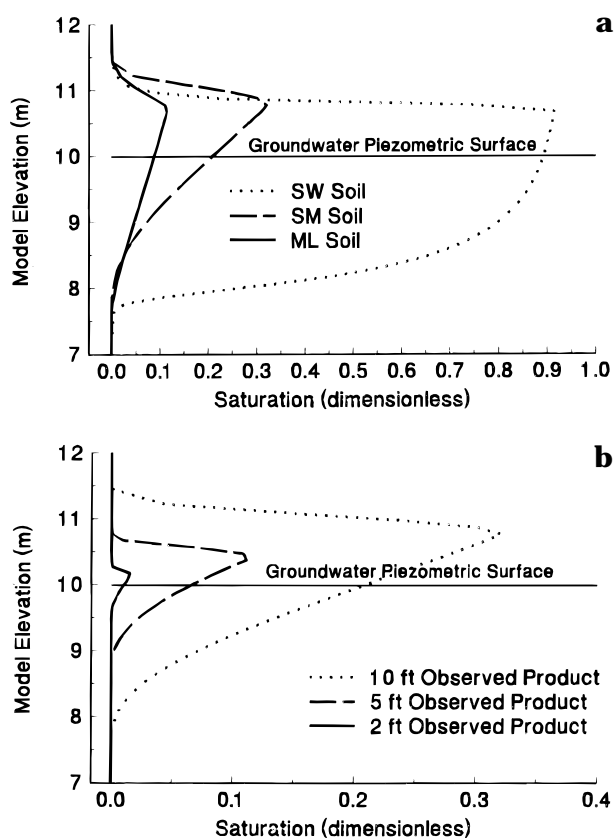


FIGURE 3. (a) Initial LNAPL saturation for 10 ft observed free product. (b) Initial LNAPL saturation for variable well thickness in the SM soil.

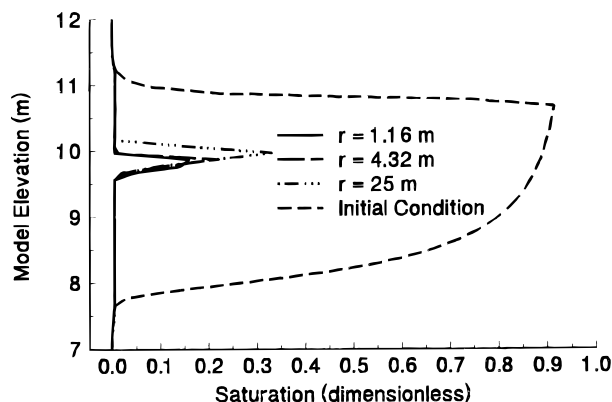
processes based on multiphase dynamics is generally lacking. Two simulations were performed for the SM and SW soil types with the vacuum applied in the capillary fringe and below the water table.

## Results

**Effect of Soil Type on Product Recovery.** Soil type exerted the strongest control on the effectiveness of hydrocarbon recovery of all of the variables considered, including the amount of groundwater drawdown and application of a vacuum to enhanced recovery. Although 10 ft of hydrocarbon was assumed to exist in the production well at the beginning

**TABLE 2. Effectiveness of Hydrocarbon Skimming for Three Soils**

soil	full domain (57.5 m radius area)			limited domain (5 m radius area)		
	hydrocarbon vol (thousands of gal)		%	hydrocarbon vol (thousands of gal)		%
SW	1920	81	96	14.4	0.35	98
SM	504	476	5.5	3.74	2.01	46
ML	252	234	7.1	1.87	0.86	54

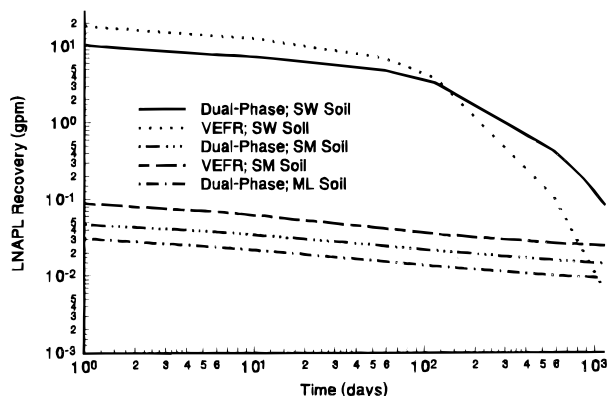


**FIGURE 4. LNAPL saturation versus model elevation in the SW soil after 3.2 yr of hydrocarbon recovery.**

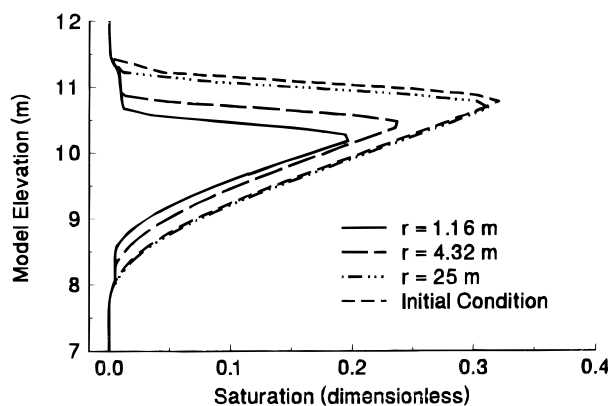
of recovery for all of the soil types, this 10 ft of thickness corresponds to widely varying hydrocarbon saturations (Figure 3a) and volumes (Table 2). Peak saturations under hydrostatic equilibrium (the initial condition) for the SW soil approach 90% (e.g., 90% of the pore space is filled with LNAPL, 10% is filled with water). The initial LNAPL volume in the full 57.5 m simulation domain for the SW soil was about 1.9 million gal (Table 2). In contrast, peak saturations in the SM soil were about 30%, with an initial volume of 0.5 million gal. The finer ML soil started with peak saturations of only 11% and a total volume of 0.25 million gal. These variations in saturations from soil to soil, due primarily to soil capillary properties, result in lower relative LNAPL permeability in the fine-grained soils. This low relative permeability, coupled with lower intrinsic permeability, results in limited LNAPL mobility and recovery in fine-grained soil.

Hydrocarbon skimming, aided by groundwater production to lower the piezometric surface, can be very effective in coarse-grained soils, such as the SW soil used for our simulations. Ninety-six percent of the hydrocarbon is predicted to be removed from the full model domain (57.5 m in radius), and 98% of the hydrocarbon is predicted to be removed from the limited domain close (within 5 m) to the well (Table 2). Hydrocarbon saturations are reduced from peak values of 90% to saturations to less than 20% within 4.3 m of the well (Figure 4). Initial LNAPL recovery rates from the skimming well are predicted to exceed 10 gal/min, decreasing to less than 1 gal/min after 3 yr of skimming (Figure 5).

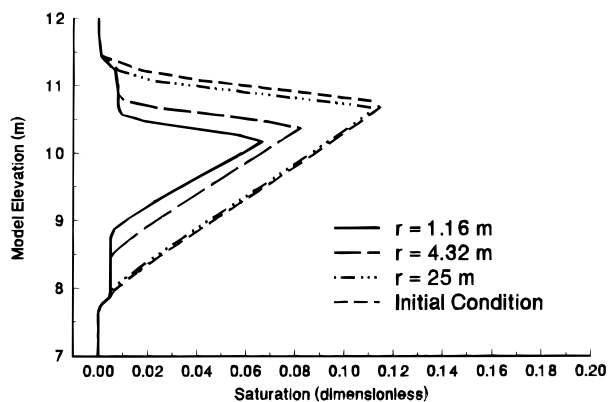
As discussed previously, initial hydrocarbon saturations within the SM soil are substantially less than in the SW soil, resulting in decreased hydrocarbon mobility. The total hydrocarbon volume in the 57.5 m model domain for the SM soil was calculated to be about one-fourth that in the SW soil (Table 2). Peak hydrocarbon saturations of 30% in the SM soil are predicted to decrease to about 10% near the well (within 1 m) after 3.2 yr of fluid recovery (Figure 6). Though the model indicates that 46% of the hydrocarbon found within



**FIGURE 5. LNAPL recovery rate through time as a function of soil type and recovery method.**



**FIGURE 6. LNAPL saturation versus model elevation in the SM soil at 3.2 yr of hydrocarbon recovery.**



**FIGURE 7. LNAPL saturation versus model elevation in the ML soil at 3.2 yr of hydrocarbon recovery.**

5 m of the well would be recovered after 3.2 yr, only about 5% of the total hydrocarbon found within the 57.5 m model domain was predicted to be recovered (Table 2). Initial LNAPL recovery rates are predicted to be about 0.045 gal/min, decreasing to less than 0.015 gal/min after 3.2 yr (Figure 5).

The ML soil has the least hydrocarbon volume within the pore space under the initial conditions (Table 2). The total domain contains only 252 000 gal of hydrocarbon, of which only 18 000 gal (7%) are predicted to be recovered after 3.2 yr of recovery. Initial peak saturations of about 11% are reduced to approximately 6% after 3.2 yr of recovery at distances in excess of 1 m from the well (Figure 7). LNAPL recovery rates start out at about 0.03 gal/min (43 gal/day) and decrease to about 0.01 gal/min (14 gal/day) (Figure 5). For both the SM and ML soil types, significant decreases in

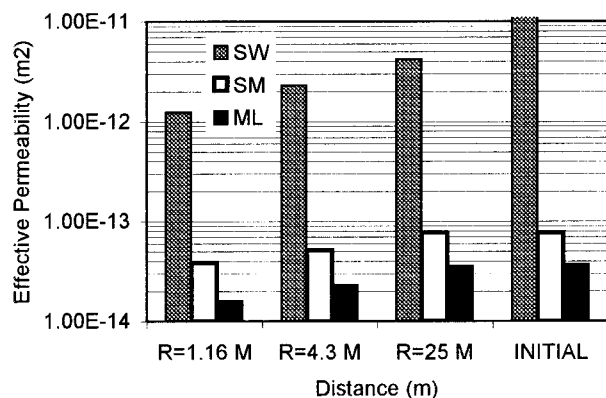


FIGURE 8. Maximum effective hydrocarbon permeability as a function of soil type and distance after 3.2 yr recovery.

hydrocarbon saturation were limited to a relatively small area around the production well. Hydrocarbon saturations 25 m from the production well were virtually unchanged after 3.2 yr of skimming in these soils (Figures 6 and 7).

A critical factor limiting the area of influence of skimming wells is the development of a low hydraulic conductivity zone (with respect to the hydrocarbon phase) near the production well. Removal of hydrocarbon from the formation decreases hydrocarbon saturations, which in turn decreases the relative permeability (and therefore LNAPL conductivity) of the soil with respect to hydrocarbon. A plot of maximum effective hydrocarbon permeability ( $k_r k_i$ ) as a function of distance from the production well (Figure 8) after 3.2 yr of hydrocarbon recovery shows that effective permeability decreases toward the well for all soil types. Effective hydrocarbon permeability can be seen to increase away from the production well. Recall that effective conductivity and permeability vary as a function of saturation, which itself varies vertically. Therefore, zones above and below the maximum conductivity zone have smaller and often negligible mobility.

**Effect of Groundwater Pumping Rates on Product Recovery.** The effect of increasing groundwater pumping and drawdown on the amount of hydrocarbon recovery was simulated by establishing a well boundary condition with 2.5, 5, 7.5, and 15 ft of groundwater drawdown and comparing the results for the SM soil. In each case, the original hydrocarbon thickness in the recovery well was 10 ft, resulting in peak hydrocarbon saturations of about 30% (Figure 3a). In all cases, the simulation was executed in a manner to remove all product that entered the well, effectively keeping the oil/air interface equal to the oil/water interface elevation in the wellbore. The formation fluids respond to the drawdown at the well at a rate controlled by the imposed gradient and the changing effective phase conductivity with respect to both hydrocarbon and water (eq 1).

Increasing the groundwater production and drawdown increases the hydraulic gradient toward the recovery well, potentially increasing the rate of LNAPL capture. However, there are several potentially negative aspects to increased groundwater production. First, increasing the drawdown can decrease hydrocarbon saturations near the well, thereby decreasing the hydraulic conductivity with respect to hydrocarbon. This can exaggerate the zone of reduced hydrocarbon conductivity near the skimming well and ultimately reduce recovery rates, as was noted to occur within 5 m of the recovery well (Table 3). Second, increasing groundwater drawdown increases groundwater production, treatment, and disposal costs. Third, increased pumping can lower the water level below the static oil/water interface, inducing hydrocarbon movement downward into previously unimpacted soils (Figure 9). If the water level subsequently rises, this hydrocarbon can become

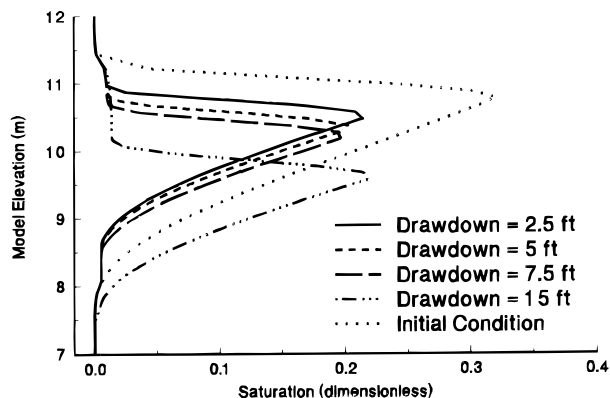


FIGURE 9. LNAPL saturation versus model elevation as a function of recovery drawdown in the SM soil at 3.2 yr.

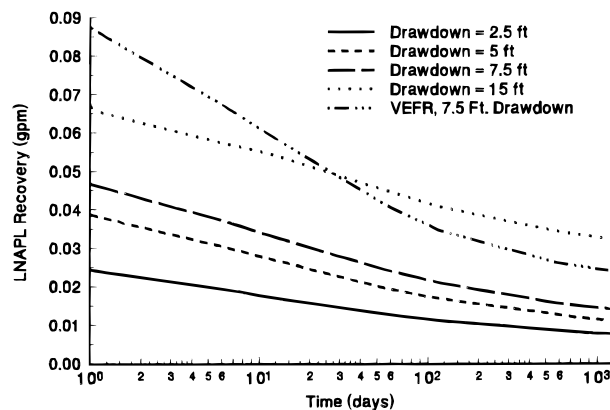


FIGURE 10. LNAPL recovery rate through time as a function of applied drawdown and vacuum in the SM soil.

TABLE 3. Hydrocarbon Recovery as a Function of Groundwater Drawdown, SM Soil

groundwater drawdown (ft)	full domain (57.5 m radius area)			limited domain (5 m radius area)		
	hydrocarbon vol (thousands of gal)		% recovery	hydrocarbon vol (thousands of gal)		% recovery
	initial	after 3.2 yr		initial	after 3.2 yr	
1.5		492	2.3	2.31	38.2	
5	504	486	3.5	2.1	43.8	
7.5		476	5.5	2	46.3	
15		444	11.9	2.3	39.6	

trapped as immobile ganglia acting as a long-term source of dissolved-phase hydrocarbons in groundwater. Since the goal of LNAPL cleanup is protection of groundwater resources and human health, it is important that these potential negative outcomes be considered in context with site closure objectives.

The effects of increased drawdown on the hydrocarbon saturation profiles in the SM soil can be seen in Figure 9. Increased drawdown did not significantly decrease peak saturations near (1.16 m) the well for this particular simulation (other soils and conditions may respond differently). Increased drawdown does, however, act to lower the profile as hydrocarbon redistributes itself vertically. Our simulations indicate that increased drawdown increases the rate of hydrocarbon recovery (Figure 10) to a certain point, particularly early in the skimming program. Increasing drawdown from 1.5 to 15 ft increases initial recovery rates from 0.025 to 0.07 gal/min (Figure 10). Total volumes of recovered hydrocarbon also increase with increasing groundwater

**TABLE 4. Effect of Initial Hydrocarbon Thickness on Recovery**

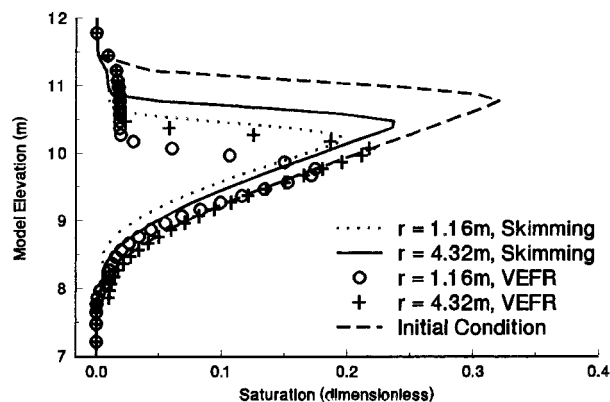
initial hydrocarbon thickness (ft)	full domain (57.5 m radius area)			limited domain (5 m radius area)		
	hydrocarbon vol (thousands of gal)			hydrocarbon vol (thousands of gal)		
	initial	after 3.2 yr	% recovery	initial	after 3.2 yr	% recovery
2	5.15	5.13	0.36	0.039	0.035	8.7
5	89	86	2.8	0.66	0.39	41
10	504	476	5.5	3.74	2.01	46

drawdown resulting from increased pumping (Table 3), except near the wellbore where less hydrocarbon is recovered at a drawdown of 15 ft.

The results suggest that there is an optimum pumping rate (corresponding to a drawdown of 7.5 ft) to maximize recovery near the production well (limited domain area, Table 3). But increasing the drawdown continuously increased the amount of recovered hydrocarbon from the full (57.5 m radius) domain. For the simulated conditions, increased groundwater drawdown might decrease the rate of recovery near the production well, but the increased drawdown enhances hydrocarbon recovery from greater distances. This points to the importance of LNAPL plume distribution and associated well field optimization in recovery system design. For example, if our simulated plume were smaller, the recovery may diminish with increasing drawdown past 7.5 ft (Table 3).

**Effect of Initial Hydrocarbon Thickness on Product Recovery.** As discussed previously, initial hydrocarbon saturations (Figure 3) can be related to the equilibrated thickness of hydrocarbon in properly screened wells. For the SM soil used in our simulations, the peak initial hydrocarbon saturation decreased from about 30% with 10 ft of hydrocarbon in the well to less than 5% with only 2 ft of hydrocarbon in the well. Decreasing the initial thickness of hydrocarbon in the recovery well from 10 to 2 ft decreases the initial volume of hydrocarbon by a factor of 100 and decreases the volume of recovered hydrocarbon by a factor of 1000 (Table 4). These outcomes exemplify the nonlinear nature of LNAPL distribution, flow, and recovery. It is interesting to note that, while geologic conditions are uniform, flow conditions are not in either the vertical or radial directions. This implies that plume and recovery “heterogeneities” exist as a result of LNAPL release and migration conditions, even in the absence of geologic variability. As most sites are geologically variable, the full complexity of LNAPL transport and cleanup becomes clear.

**Effect of Vacuum-Enhanced Fluid Recovery (VEFR).** Vacuum-enhanced fluid recovery (VEFR) and its related counterparts (e.g., bioslurping, drop-tube recovery, etc.) involve application of a vacuum to fluid recovery wells during ongoing liquid phase pumping. This vacuum acts to (1) increase the effective gradient toward a recovery well, thereby increasing rates of fluid capture; (2) capture hydrocarbons from the zone at and above the oil/air interface in the well, thereby mobilizing hydrocarbon from a zone where some of the highest hydrocarbon saturations are held by capillary forces; (3) increase rates of volatilization of hydrocarbon, thereby increasing mass rates of removal from the system. VEFR is, in effect, the simultaneous application of soil vapor extraction and hydrocarbon skimming using the same recovery well. The present simulations investigate the effects of VEFR on the fluid-phase hydrocarbon recovery. That is, for this study we are not interested in the effects of volatilization and recovery of vapor-phase hydrocarbons, and those conditions were not simulated. For volatile LNAPLs,



**FIGURE 11. LNAPL saturation with model elevation comparing the effects of skimming to VEFR at 3.2 yr.**

**TABLE 5. Hydrocarbon Recovery Using Skimming with and without VEFR**

soil	full domain (57.5 m radius area)			limited domain (5 m radius area)			
	hydrocarbon vol (thousands of gal)			hydrocarbon vol (thousands of gal)			
	initial	after 3.2 yr	% recovery	initial	after 3.2 yr	% recovery	
SW	skimming	1920	81	96	14.4	0.35	98
	VEFR		40	98		0.31	98
SM	skimming	504	476	5.5	3.74	2.01	46
	VEFR		456	9.5		1.8	51

the total mass recovery (vapor + LNAPL) under VEFR will be greater than the fluid recoveries alone reported here.

Comparison between hydrocarbon recovery rates from simple skimming and from VEFR (Figures 5 and 10) shows that VEFR substantially increases rates of fluid-phase hydrocarbon recovery, particularly early in the remediation period. The effect on the saturation profiles is significant in fine-grained materials (Figure 11) but less so in coarser-grained materials, such as the SW soil modeled. Most notable is the sharp decrease in saturation in the upper part of the hydrocarbon profile relative to the results of fluid recovery without vacuum enhancement. Like increasing the rate of drawdown, the application of a vacuum to the production well nearly doubles the percentage of hydrocarbon recovered (Table 5), but unlike increasing the drawdown, it does not encourage the downward movement of hydrocarbon into previously unimpacted soils.

**Summary and Conclusions**

The relationship between LNAPL saturation and LNAPL hydraulic conductivity is critical in assessing the viability of an LNAPL recovery system. Because the relative permeability of soil toward LNAPL decreases with decreasing saturation and because the intrinsic permeability of fine-grained soils is less than that of coarse-grained soils, free-product pumping or skimming has less likelihood of success in fine-grained soil. Furthermore, for any soil type, recovery decreases LNAPL saturation and relative permeability near the well—resulting in a lower permeability region that retards recovery from greater distances (Figure 8).

Evaluations using MAGNAS3 (1, 2, 3) showed that recovery of hydrocarbon in fine-grained soils was limited, with significant reductions in LNAPL saturation occurring only within about 10–15 ft of the well. Although the ML and SM soils were texturally different, total percent recoveries were

similar. This suggests that silt and clay fractions can act to reduce LNAPL recovery and mobility even if the sand fraction is significant (e.g., 65% in the SM soil). Recovery of LNAPL in coarse-grained soils was predicted to be much more successful, with approximately 95% of the original hydrocarbon recovered through fluid pumping. However, all soils contained LNAPL saturations of concern (greater than 15% in the SW soil) after 3.2 yr of remediation. Since LNAPL recovery decreases through time, hydrocarbon can persist even in the coarsest soil. Since coarse soils generally allow the greatest advective solute transport, the greatest risk may be presented by these soils even though skimming is the most successful from a volumetric recovery perspective.

Increased drawdown in the recovery well increases the total volume of hydrocarbon recovered in fine-grained soils but causes downward migration of hydrocarbon and contamination of previously unimpacted soils. It also diminishes total recovery near the well for the conditions modeled, and total production will theoretically diminish once the benefits of an increased gradient are eliminated by an area of low effective hydrocarbon conductivity. Application of a vacuum to the extraction well (VEFR) similarly increased the rate of hydrocarbon recovery, without the associated impacts to previously unimpacted soils.

The effectiveness of skimming declines markedly with decreases in the initial measured thickness of hydrocarbon in an extraction or monitoring well. This is a result of significantly smaller hydrocarbon saturations, volume, and mobility with decreasing observed thickness.

#### Supporting Information Available

An appendix containing text and equations about the multiphase theory and model setup and boundary conditions (4 pp) will appear following these pages in the microfilm edition of this volume of the journal. Figures to enhance the visualization of the multiphase effects are available in color on the World Wide Web. Photocopies of the Supporting Information from this paper or microfiche (105 × 148 mm, 24× reduction, negatives) may be obtained from Microforms Office, American Chemical Society, 1155 16th St. NW,

Washington, DC 20036. Full bibliographic citation (journal, title of article, names of authors, inclusive pagination, volume number, and issue number) and prepayment, check or money order for \$13.50 for photocopy (\$15.50 foreign) or \$12.00 for microfiche (\$13.00 foreign), are required. Canadian residents should add 7% GST. Supporting Information is also available via the World Wide Web at URL <http://www.chemcenter.org>. Users should select Electronic Publications and then Environmental Science and Technology under Electronic Editions. Detailed instructions for using this service, along with a description of the file formats, are available at this site. To download the Supporting Information, enter the journal subscription number from your mailing label. For additional information on electronic access, send electronic mail to [si-help@acs.org](mailto:si-help@acs.org) or phone (202)872-6333.

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