Determining the thickness of LNAPL-impacted soils considering water table fluctuations

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ABSTRACT
Monitoring of the water table and apparent thickness of Light Non Aqueous Phase Liquid (LNAPL), at an observation well, was carried out over a period of 4 months prior to in situ treatment of contaminated soils. Data collected from the monitoring program was used to determine the thickness of soils impacted by LNAPL, as well as the vertical location of impacted soils within the geological formation. The thickness of impacted soils was determined by considering the presence of the free phase of LNAPL in the soils and the residual LNAPL potentially contained in the soils. This determination was performed by taking into account water table fluctuations which can affect the location of the free phase of LNAPL and residual LNAPL in the soils. Determining total thickness of soils impacted by a LNAPL is a useful element during the assessment of the impacted soil volumes and could allow a better precision of in situ treatment of soils. Moreover, this evaluation could be used to determine how deep the water table should be lowered, through pumping, in order that the impacted soils become located in an unsaturated zone and can be then subjected to an in situ treatment by ventilation or by thermal approach.

RÉSUMÉ
Un suivi de la profondeur de l'eau et de l'épaisseur apparente d'un Liquide Immiscible Léger (LIL) identifié dans un puits d'observation a été effectué pour une période de 4 mois préalablement à un traitement *in situ* de sols contaminés. Les données collectées ont été utilisées pour déterminer l'épaisseur des sols affectés par le LIL, ainsi que la localisation verticale des sols affectés dans la formation géologique. Cette détermination prend en compte la présence de LIL libre et le LIL résiduel dans les sols. L'épaisseur des sols affectés a été déterminée en tenant en compte des fluctuations de la nappe d'eau qui affectent les localisations du LIL libre et le LIL résiduel présents dans les sols. L'évaluation de l'épaisseur des sols affectés par le LIL constitue un élément très utile lors de l'évaluation des volumes des sols affectés par le LIL et permettrait de viser les sols affectés d'une manière plus précise lors d'un traitement *in situ*. Cette évaluation permettrait de déterminer à quelle profondeur la nappe d'eau devrait être abaissée par pompage d'eau, si les sols affectés sont totalement ou partiellement dénoyés dans la nappe d'eau, afin que les sols affectés soient localisés dans la zone non-saturée et être soumis par exemple à un traitement *in situ* par approche de ventilation ou thermique.

1 INTRODUCTION

Environmental site characterization studies, conducted following petroleum hydrocarbon spills, usually involve borehole drilling and observation well installation to characterize soils and groundwater, which includes estimating the extent of soils impacted by petroleum hydrocarbons. Estimating the thickness of impacted soils is a fundamental aspect when assessing the volume of impacted soils and/or the eventual establishment of in situ treatment systems. Many studies have based the evaluation of the thickness of Non Aqueous Phase Liquid (NAPL) impacted soils on the thicknesses of NAPL measured in observation wells (Farr et al. 1990, Lenhard and Parker 1990, NGWA 1992a, 1992b). Furthermore, other works have focused specifically on the characterization of sites contaminated by Light Non Aqueous Phase Liquid (LNAPL) and their recovery (EPA 1996, Charbeneau et al. 1999, Charbeneau 2000). The LNAPL present in soils can be found at varying saturation. Part of the LNAPL may be at a high saturation enough to allow it to flow easily within a porous medium, if it is subjected to hydraulic gradients. Under this condition, the LNAPL refers as a free LNAPL which can thus enter in the observation well if the LNAPL is in contact with the screened section of the observation well. A large proportion of the LNAPL present in soils can however be immobile if it is at residual saturation. Residual LNAPL is trapped in soils following the free LNAPL transport, which can occur in a number of situations, including: 1) in the LNAPL flowing pathways during the transport of LNAPL from the ground surface to the water table; 2) above and below a free LNAPL lens according to water table fluctuations and 3) after the pumping recovery of the free LNAPL (Charbeneau et al. 1999, 2000, Lefebvre 2010). Consequently, an adequate assessment of the thickness of soils impacted by LNAPL should include: 1) determining free LNAPL thickness in soils and 2) determining thickness of soils containing residual LNAPL occurring potentially along all pathways where the free LNAPL has passed during its transport within the geological formation.

This article presents a case study of determining the thickness of soils impacted by LNAPL (Hereinafter mentioned as « impacted soils ») at an observation well by considering the water table fluctuations, which affect the location of the free and residual LNAPL in soils. This assessment only considers that the LNAPL has been presented in the monitored well according only to lateral transport within the geological formation, and does not consider vertical LNAPL migration pathways, particularly from the ground surface to water table.

2 ISSUE

Two important elements should be considered when assessing the thickness of impacted soils. These two elements are described below:

1) The apparent LNAPL thickness in the observation well is impacted by the water table fluctuations. This means that an ascending water table will cause a decrease in the apparent LNAPL thickness in the observation well, while a descending water table will increase the apparent LNAPL thickness in the observation well (Yaniga 1984, Hunt et al. 1989, Kemblowski and Chiang 1990, Marinelli and Durnford 1996, Liao and Aral 1999). Consequently, the apparent LNAPL thickness in the observation well is generally not in equilibrium with the LNAPL thickness in the geological formation. In such a situation, apparent LNAPL thickness measurements in the observation well may lead to an erroneous assessment of the free LNAPL thickness in soils (Kemblowski and Chiang 1990). Therefore, the method of evaluating the free LNAPL thickness in soils needs to consider the apparent LNAPL thickness measured in the observation well relative to the true LNAPL thickness observed within the geological formation.

2) The location of the free LNAPL within the geological formation is relatively sensitive to water table fluctuations. An evaluation of the free LNAPL thickness within the geological formation based on a specific point in time, does not account for smearing of LNAPL that can occur with seasonal or other water table fluctuations, and as a result, the thickness of impacted soils may be underestimated. The fact that there is a change in the vertical location of the free LNAPL in the geologic formation according to the water table fluctuations, a range of soils potentially containing residual LNAPL should then occur. Indeed, if the water table drops, the residual LNAPL will be trapped in the unsaturated zone of the aquifer, whereas when the water table rises, the residual LNAPL will be trapped in the saturated zone of the aquifer. This phenomenon causes an increase of the impacted soils thickness. The impact of the movement of free LNAPL within the geological formation relative to the water table fluctuations needs to be considered when evaluating the total thickness of impacted soils.

3 COLLECTED DATA AND THE OBSERVED BEHAVIOR DURING MONITORING

The water table and apparent thickness of LNAPL in an observation well were monitored over a period of 4 months to evaluate the total thickness of impacted soils by considering the periodic water table fluctuations within the geological formation. A total of 15 surveys were conducted between November 11th of 2013 and February 27th of 2014. These surveys were carried out following an accidental spill of petroleum hydrocarbons that occurred in the Grenoble region of France in 2013. It should be mentioned that the observation well used in this study was installed before the accidental spill. Subsequent to the accidental spill, additional observation wells were installed at the site as part of an environmental characterization study being carried out prior to in situ treatment of contaminated soils.

The investigated observation well has a diameter of 51 mm and was completed to a depth of 5.2 m below ground surface. According to the obtained information, the screened section placed in the lower part of the observation well has been installed with a considerable length that should never be completely submerged in the groundwater. Even at the highest water table level, the LNAPL would always be below the top of the screened section of the monitored well, thus allowing the free LNAPL to absolutely penetrate inside the observation well. Furthermore, the observation well was completed with a flush mount casing with a top of the PVC riser measured 2 cm below the ground surface. The geological description is based on the stratigraphy logged at a borehole located 1 meter from the observation well used in this study. The geological formation of site consists of 1.5 m of heterogeneous backfill, composed mainly of a layer of sand with pebbles and sometimes a little clay underlain by native sand to at least the base of the observation well.

As presented in Figure 1, the depth of groundwater and the apparent LNAPL thickness within the observation well were fluctuated throughout the monitored period (November 11th of 2013 and February 27th of 2014). The depth of groundwater generally ranged from 3.23 to 3.69 m below the ground surface. For its part, the measured thickness of free LNAPL (apparent thickness) was ranged between 0.32 and 0.70 m. Accordingly, the LNAPL was localised within the native sand unit of geological formation. On the other hand, Figure 1 shows that fluctuations in both depth of groundwater and apparent LNAPL thickness were produced during the groundwater monitoring period.

LNAPL periodic recovering operations were conducted during the monitoring period using some existing observation wells localised on site. However, these observation wells that were used in the recovery operations were localised distant to the monitored well used in this study, and the water level within the monitored well was not affected by the recovery operations. On the other hand, the LNAPL fluctuations (change in LNAPL thickness) recorded within the monitored well do not indicate that a significant decrease in the free LNAPL thickness has occurred within the monitored well. In fact, the largest apparent LNAPL thicknesses were noted at the end of the groundwater monitoring (Figure 1). This indicates that apparent LNAPL thicknesses were likely influenced by the water table fluctuations. Furthermore, it is observed that there is generally an inverse relationship between the depth of groundwater and the apparent LNAPL thickness in the observation well (Figure 1). This observation has already been noted in other studied sites conducted by other groups of researchers (Hunt et al. 1989, Kemblowski and Chiang 1990, Marinelli and Durnford 1996, Liao and Aral 1999). The observed fluctuations in depth of groundwater and apparent LNAPL thickness during the groundwater monitoring carried out between November 2013 and February 2014 are taken into account in order to better evaluate the total thickness of the impacted soils.

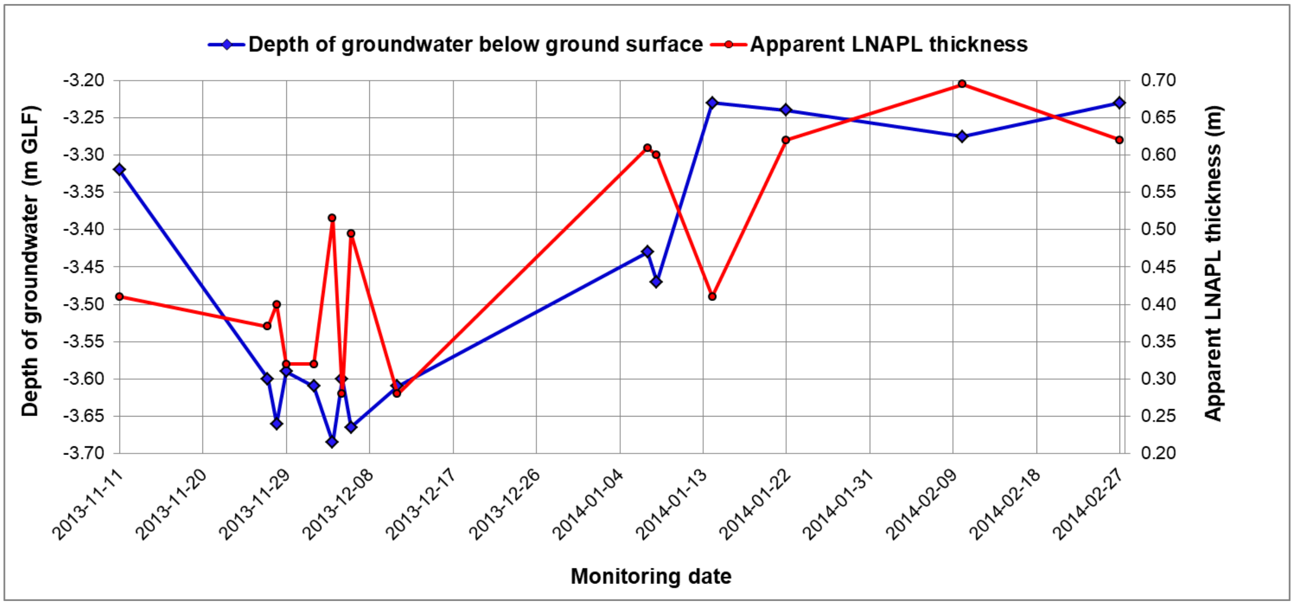

Figure 1. Depth to water and apparent LNAPL thickness variations in the investigated well

4 METHODOLOGY

In order to evaluate the total LNAPL thickness in soils, the model presented by Lefebvre and Boutin (2000) was used. This model (Figure 2) shows the LNAPL distribution in the soils and in the screened casings (equivalents of observation wells), thus considering the capillary behavior of the Air-LNAPL and LNAPL-Water systems because the LNAPL is present between air and water. This capillary behavior is developed according to the capillarity model of Brooks and Corey (1964). To simplify the representation of the capillary properties, fluid heights have been used for the different systems concerned. The pertinence of the model's concepts showed in Figure 2, relative to the objective of this work, is in determining the displacement heights for the different systems that constitute the key-aspects for evaluating total thickness of LNAPL in soils (h_{Nt}). According to Lefebvre (2010), h_{Nt} can be estimated by the sum of the thickness of free LNAPL (h_N) in soils and the displacement height of Air-LNAPL (h_d^{AN}) as presented in equation 1. It should be noted that h_d^{AN} also represents the height of the soils where the LNAPL is retained by capillary force and moved under the effect of a hydraulic gradient (in LNAPL), according to Darcy's law in its generalized form for multiphasic flow. This retained LNAPL by capillarity should not be considered as a residual LNAPL because it can easily flows into the soils.

$$h_{Nt} = h_N + h_d^{AN} \qquad [1]$$

Descriptions of the methods that can be used to determine h_N and h_d^{AN} are discussed in the following subsections. The last subsection (4.3) presents how to calculate the elevations (top and bottom) of the total LNAPL thickness in soils. These elevations make it possible to determine the location of the impacted soils relative to the ground surface.

4.1 Calculating free LNAPL height in soils (h_N)

It is often considered that there is a linear relationship between the apparent LNAPL thickness in the observation well and in the geological formation, based on the idea that there is a physical equilibrium between these two phases (Lenhard and Parker 1987, 1988, Parker et al. 1987, Liao and Aral 1999). However, analysis of the capillary behavior of soils surrounding the observation well has shown that the apparent LNAPL thickness detected in the observation well is not similar to that in the geological formation (Gruszcenski 1987, Hughes et al. 1988, Hayes et al. 1989). It is therefore assumed that the apparent LNAPL thickness measured in an observation well would not be representative of the actual LNAPL thickness in soils.

There are two empirical methods for assessing the actual LNAPL thickness in soils based on the Bail-Down test conducted in an observation well (Gruszcenski 1987, Hughes et al. 1988). However, this type of test would need to be conducted with each monitored event to assess the thickness of LNAPL as it varies with the fluctuation of the water table and would result in additional time on site, additional data analysis, and the potential need to manage impacted groundwater with each monitored event. The model proposed by Lefebvre and Boutin (2000), as well as the equations found in Lefebvre (2010) are used to assess the thickness of LNAPL in soil by using water level and LNAPL level measurements in the observation well resulting in less time on site, less data processing, and no need to manage impacted groundwater. According to Lefebvre (2010), the thickness of free LNAPL h_N in soils is the interval where LNAPL is present in soils at a pressure that is equal to or greater than atmospheric pressure. The thickness of LNAPL h_N in soils can be related to the apparent LNAPL thickness in the well (H_N) and to the displacement height in the LNAPL-Water system (h_d^{NW}) as presented in equation 2.

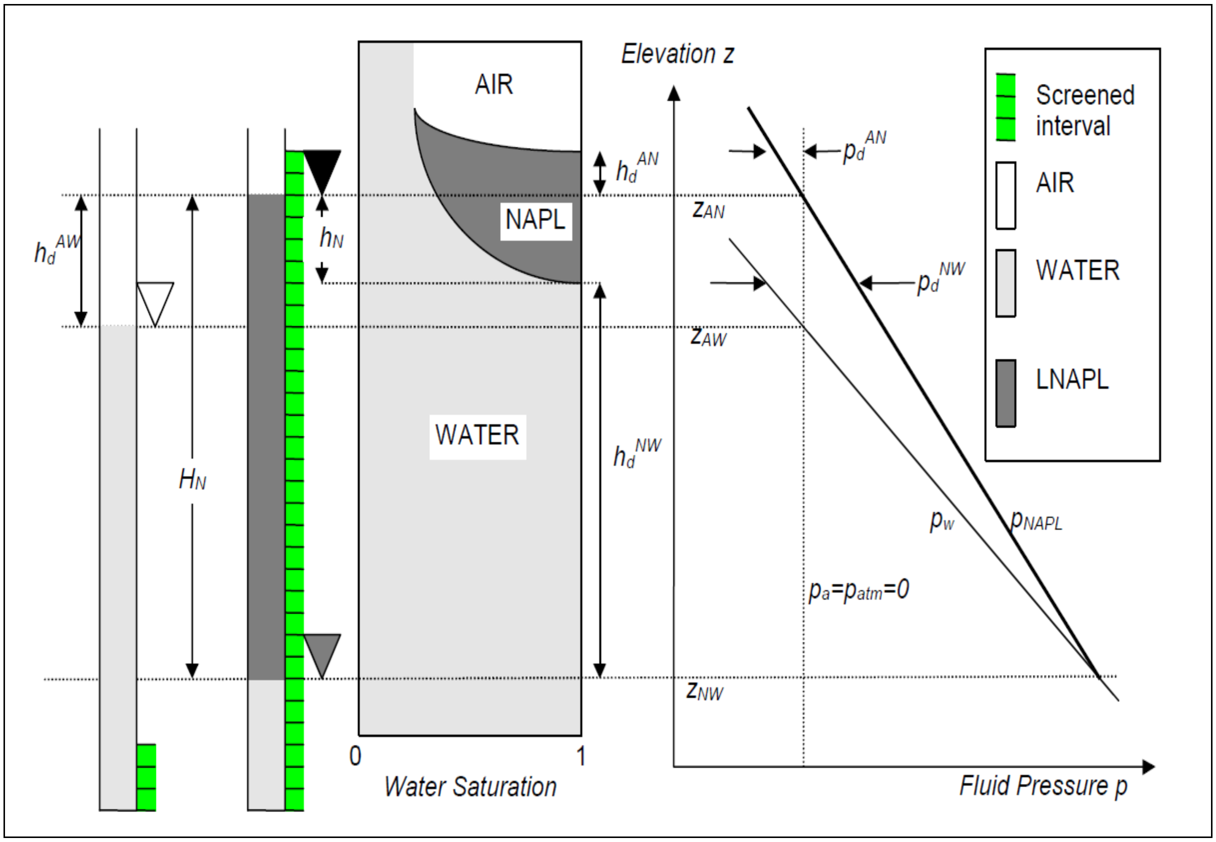

Figure 2. Equilibrium fluid distribution in soils adjacent to a well containing free LNAPL (Lefebvre and Boutin 2000)

$$h_N = H_N - h_d^{NW} \qquad [2]$$

H_N thickness was measured during each groundwater monitoring event. The displacement height h_d^{NW} could be calculated according to equation 3, where ρ_W and ρ_N represent the density of water (1000 kg/m^3) and the density of LNAPL (690 kg/m^3 has been determined in the laboratory), respectively, while the gravitational acceleration (g) is 9.81 m/s^2.

$$h_d^{NW} = \frac{P_d^{NW}}{(\rho_W - \rho_N)g} \qquad [3]$$

According to equation 3 and the available data, the displacement pressure of LNAPL-Water (P_d^{NW}) remains to be determined. This could be calculated according to the displacement pressure equation, for capillary tubes, applied to the LNAPL-Water (NW) and Air-Water (AW) systems, which is expressed as follows:

$$P_d^{NW} = P_d^{AW} . \frac{\sigma_{NW} \cos \theta_{NW}}{\sigma_{AW} \cos \theta_{AW}} \qquad [4]$$

In practice, the contact angle θ is rarely considered explicitly when converting capillary pressures between different fluid systems (Parker 1989, Lenhard and Parker 1990, Charbeneau et al. 1995). This involves the assumption that the fluid is perfectly wetting, where $\theta = 0°$ ($\cos \theta = 1$), for all considered fluid systems. On the other hand, the interfacial tensions (σ) are always used in equation 4. For this purpose, the values of the interfacial tension considered for the LNAPL-Water (σ_{NW}) and Air-Water (σ_{AW}) systems are respectively of 48 mN/m and 72 mN/m (Lefebvre 2010). With these data, the displacement pressure Air-Water (P^d_{AW}) remains to be determined.

The LNAPL displacement pressure Air-Water (P^d_{AW}) can be determined by calculating the LNAPL displacement height of Water-Air (h_d^{AW}). According to the Lefebvre and Boutin (2000) model shown in Figure 2, the displacement height of Water-Air (h_d^{AW}) represents the distance between the LNAPL elevation in the well and the initial elevation of water table (without effect or pressure from LNAPL). The LNAPL elevation in the well may be determined by considering the LNAPL depths relative to the elevation of the top of the PVC's well (Z_{PVC}). For its part, the initial elevation of the water table can be determined theoretically by using the equation of Testa and Winegardner (1991). This equation allows correcting the depth of groundwater in a well to the static water table in a well according to the apparent LNAPL thickness and density of LNAPL. The equation of Testa and Winegardner (1991) is expressed as follows:

$$CDTW = Static\ DTW - (PTap\,.\,G) \quad [5]$$

Where:
CDTW : Corrected depth of water table
DTW : Measured depth of groundwater
PTap : Apparent LNAPL thickness
G : Density of LNAPL

Since the elevation of the top of the well (Z_{PVC}) is known (209.10 m to General Levelling of France (GLF)), the corrected depth of the water table (*CDTW*), being determined according to equation 5, could be converted to elevation, which represents the initial elevation of the water table (Z_{CDTW}). It should be mentioned here that the data concerning the measured depth of groundwater (*DTW*) and the apparent LNAPL thickness in the observation well (*PTap* – indicated also as H_N in equation 2) were collected during the surveys carried out as part of the 2013/2014 groundwater monitoring events. For its part, the density of LNAPL present in the observation well (*G* – indicated also as ρ_N in equation 3) is of 690 kg/m^3. The initial elevation of the water table (Z_{AW}) and that of the LNAPL in the observation well (Z_{AN}) are the values allowing for the calculation of the displacement height h_d^{AW}, as presented in equation 6. Once h_d^{AW} is calculated, it can be converted to a displacement pressure (P^d_{AW}) with a conversion factor of 98.1 Pa/cm of water (eg. for a displacement height of 68 cm, P^d_{AW} would be of 6.68 kPa).

$$h_d^{AW} = Z_{AN} - Z_{AW} \quad [6]$$

4.2 Calculating displacement height h_d^{AN}

In order to evaluate the displacement height h_d^{AN}, equation 7 was used, where ρ_N and ρ_A represent respectively the densities of LNAPL and of Air, while *g* represents the gravitational acceleration. The air density, being very low compared to that of water, has been neglected.

$$h_d^{AN} = \frac{P_d^{AN}}{(\rho_N - \rho_A)\,g} \approx \frac{P_d^{AN}}{\rho_N\, g} \quad [7]$$

For equation 7, the displacement pressure of the Air-LNAPL system (P_d^{AN}) is unknown, but could be calculated by using the displacement pressure equation, for capillary tubes, applied to systems of Air-LNAPL (AN) and Air-Water (AW) which is expressed as follows:

$$P_d^{AN} = P_d^{AW} \cdot \frac{\sigma_{AN}\cos\theta_{AN}}{\sigma_{AW}\cos\theta_{AW}} \quad [8]$$

As already mentioned in section 4.1, the contact angle θ is rarely considered explicitly when converting capillary pressures between different fluid systems. Therefore, θ was assumed equal to 0° for all fluid systems considered.

For the interfacial tensions (σ), used in equation 8, of the Air-LNAPL (σ_{AN}) and Air-Water (σ_{AW}) systems, they are considered to be respectively of 20 mN/m and 72 mN/m (Lefebvre 2010). With these values concerning the contact angles, the interfacial tensions and the value of the displacement pressure P_d^{AW} already calculated (section 4.1), the displacement pressure P_d^{AN} can be calculated, according to equation 8, and subsequently be introduced in equation 7 to evaluate h_d^{AN}.

4.3 Determining elevations corresponding to top and bottom of the total LNAPL thickness

In order to determine the location of the impacted soils, the elevation of the top of the total LNAPL thickness in soils (ZH_{hNt}), as well as the elevation of the bottom of the total LNAPL thickness in soils (ZB_{hNt}) are respectively determined according to equations 9 and 10, where Z_{AN} represents the LNAPL elevation in the observation well (see Figure 2), h_d^{AN} is the displacement height of LNAPL-Air and h_N is the actual free LNAPL thickness in soils.

$$ZH\,h_{Nt} = Z_{AN} + h_d^{AN} \quad [9]$$

$$ZB\,h_{Nt} = Z_{AN} - h_N \quad [10]$$

5 PROCESSING, RESULTS AND DISCUSSION

The measured LNAPL depth ($P_{LNAPL/PVC}$) and depth of water (*DTW*) collected from the monitored well are presented in Table 1. This table also includes the obtained results for the LNAPL displacement pressures (P_d^{AW}, P_d^{NW} and P_d^{AN}) and LNAPL displacement heights (h_d^{AW}, h_d^{NW} and h_d^{AN}) for the considered fluid systems. These results are obtained by following the methodological descriptions described in the previous section (section 4). These results made it possible to evaluate the total LNAPL thicknesses in soils (h_{Nt}) by using the data collected from each of the 2013/2014 monitoring events, as well as elevations corresponding to the top and bottom of LNAPL thickness.

According to Table 1, the total thickness of LNAPL in soil (h_{Nt}) for a given monitoring event ranged from 0.13 (December 5, 2013) to 0.32 m (February 10, 2014). The water table fluctuations have increased the free LNAPL phase in soils to an elevation of 206.63 m GLF (February 10, 2014), while the lowest elevation where free LNAPL in soils was measured, was 205.70 m GLF (December 11, 2013). Accordingly, the total thickness of the impacted soils at the investigated well is 0.93 m (206.63 m GLF - 205.70 m GLF). As the elevation of the ground surface is of 209.12 m GLF, the impacted soils are located at a depth of 2.50 m (209.12 m GLF - 206.63 m GLF) to 3.42 m below ground surface (209.12 m GLF - 205.70 m GLF). It should be noted that the thickness of impacted soils was based only on 15 surveys. Since these surveys were carried out on irregular periods, it is assumed that other fluctuations could have occurred during the groundwater monitoring period but were not covered by the surveys.

Table 1. Data collected during the groundwater monitoring carried out in 2013/2014 and obtained results following the data processing.

Data	Depth LNAPL /PVC	LNAPL elevation	Water table depth/ PVC	Appar. LNAPL thickn.	Correc. depth of water table	Initial elevation of water table	Displ. height Water-Air	Displ. pressure Water-Air	Displ. pressure LNALP-Water	Displ. height LNAPL-Water	Actual LNAPL thick. In soils	Displ. Pressure NALP-Air	Displ. height LNAPL-Air	Total LNAPL thich. in soils	Elevation of top of h_{Nt}	Elevation of the bottom of h_{Nt}
Prefix	$P_{LIL/PVC}$	Z_{AN}	*DTW*	H_N	*CDTW*	Z_{AW}	h_d^{AW}	P_d^{AW}	P_d^{NW}	h_d^{NW}	h_N	P_d^{AN}	h_d^{AN}	h_{Nt}	ZH_{hNt}	ZB_{hNt}
Unit	(m)	(m GLF)	(m)	(m)	(m)	(m GLF)	(m)	(kPa)	(kPa)	(m)	(m)	(kPa)	(m)	(m)	(m GLF)	(m GLF)
Equ. Nr in the text	-	-	-	-	5	-	6	-	4	3	2	8	7	1	9	10
2013-11-11	2.89	206.21	3.30	0.41	3.02	206.08	0.13	1.25	0.83	0.27	0.14	0.35	0.05	0.19	206.26	206.07
2013-11-27	3.21	205.89	3.58	0.37	3.32	205.77	0.11	1.12	0.75	0.25	0.12	0.31	0.05	0.17	205.94	205.77
2013-11-28	3.24	205.86	3.64	0.40	3.36	205.74	0.12	1.22	0.81	0.27	0.13	0.34	0.05	0.18	205.91	205.73
2013-11-29	3.25	205.85	3.57	0.32	3.35	205.75	0.10	0.97	0.65	0.21	0.11	0.27	0.04	0.15	205.89	205.74
2013-12-02	3.27	205.80	3.59	0.32	3.37	205.73	0.10	0.97	0.65	0.21	0.11	0.27	0.04	0.15	205.87	205.72
2013-12-04	3.15	205.95	3.66	0.51	3.31	205.79	0.16	1.57	1.04	0.34	0.17	0.43	0.06	0.24	206.01	205.78
2013-12-05	3.30	205.80	3.58	0.28	3.39	205.71	0.09	0.85	0.57	0.19	0.09	0.24	0.03	0.13	205.83	205.71
2013-12-06	3.15	205.95	3.64	0.49	3.30	205.80	0.15	1.50	1.00	0.33	0.16	0.42	0.06	0.23	206.01	205.78
2013-12-11	3.31	205.79	3.59	0.28	3.40	205.70	0.09	0.85	0.57	0.19	0.09	0.24	0.03	0.13	205.82	205.70
2014-01-07	2.80	206.30	3.41	0.61	2.99	206.11	0.19	1.85	1.24	0.41	0.20	0.52	0.08	0.28	206.38	206.10
2014-01-08	2.85	206.25	3.45	0.60	3.04	206.06	0.19	1.82	1.22	0.40	0.20	0.51	0.07	0.27	206.32	206.05
2014-01-14	2.80	206.30	3.21	0.41	2.93	206.17	0.13	1.25	0.83	0.27	0.14	0.35	0.05	0.19	206.35	206.16
2014-01-22	2.60	206.50	3.22	0.62	2.80	206.31	0.19	1.88	1.26	0.41	0.21	0.52	0.08	0.28	206.58	206.29
2014-02-10	2.56	206.54	3.25	0.69	2.77	206.32	0.21	2.11	1.41	0.46	0.23	0.59	0.09	0.32	206.63	206.31
2014-02-27	2.59	206.51	3.21	0.62	2.78	206.32	0.19	1.88	1.26	0.41	0.21	0.52	0.08	0.28	206.59	206.30

The total thickness of impacted soils (0.93 m) is evaluated according to the thickness of free LNAPL present in soils and while also considering the thickness of soils potentially containing residual LNAPL. The presence of residual LNAPL in the soils was assigned to all pathways where the free LNAPL passed during its transport. This hypothesis was followed considering that the residual saturation of LNAPL in the soils surrounding the investigated observation well is considerable. To this purpose, Cohen and Mercer (1993) set a value of 0.18 L/m^3 for residual saturation of LNAPL in soils. This value reinforces our hypothesis that our impacted soils may actually have a residual LNAPL retention capacity. Figure 3 shows the evolution of the residual LNAPL phase in soils and also shows the vertical location of the total LNAPL thickness in soils (h_{Nt}) determined during the groundwater monitoring carried out between November 11th of 2013 and February 27th of 2014.

According to Figure 3, the conceptualization of the residual phase begins since the second survey carried out on November 27th of 2013 following the displacement of the free LNAPL from top to bottom, creating thus a residual phase of 32.5 cm, that is the difference in elevation between the top of the LNAPL assessed during the survey of November 11th of 2013 (206.26 m GLF) and the top of the LNAPL evaluated during the survey conducted on November 27th of 2013 (205.94 m GLF). During the third survey, the LNAPL has moved again from top to bottom, forming thus a residual LNAPL phase of 35.1 cm, corresponding to difference in elevation between the top of the LNAPL assessed during the survey of November 11th, 2013 (206.26 m GLF) and the top of the LNAPL evaluated during the survey conducted on November 28th of 2013 (205.91 m GLF). It should be noted that the residual LNAPL determined previously is incorporated in the residual LNAPL phase evaluated during the survey of November 28th, 2013. It is by following this process that the evolution of the residual LNAPL phase in soils has been established in this study. According to Figure 3, it can be seen that the LNAPL displacement have all been produced in the native sand unit. This therefore limits a possible comparison between the LNAPL behavior in this soil and the overlying heterogeneous backfill. Figure 3 shows also that the impacted soils can be located in the unsaturated zone, as noted on December 5th of 2013, where the residual LNAPL phase is determined in the unsaturated zone. For this situation, an in situ soil treatment by the thermal approach, for example, would be easily applicable. On the other hand, the impacted soils can be located in the saturated zone, as recorded on February 10th of 2014, where the residual LNAPL phase is determined in the saturated zone (Figure 3). In this situation, the obtained results make it possible to determine how deep the water table should be lowered, through pumping, in order that the impacted soils become located in an unsaturated zone and can then be subjected to an in situ treatment by, for example, ventilation or by thermal approach.

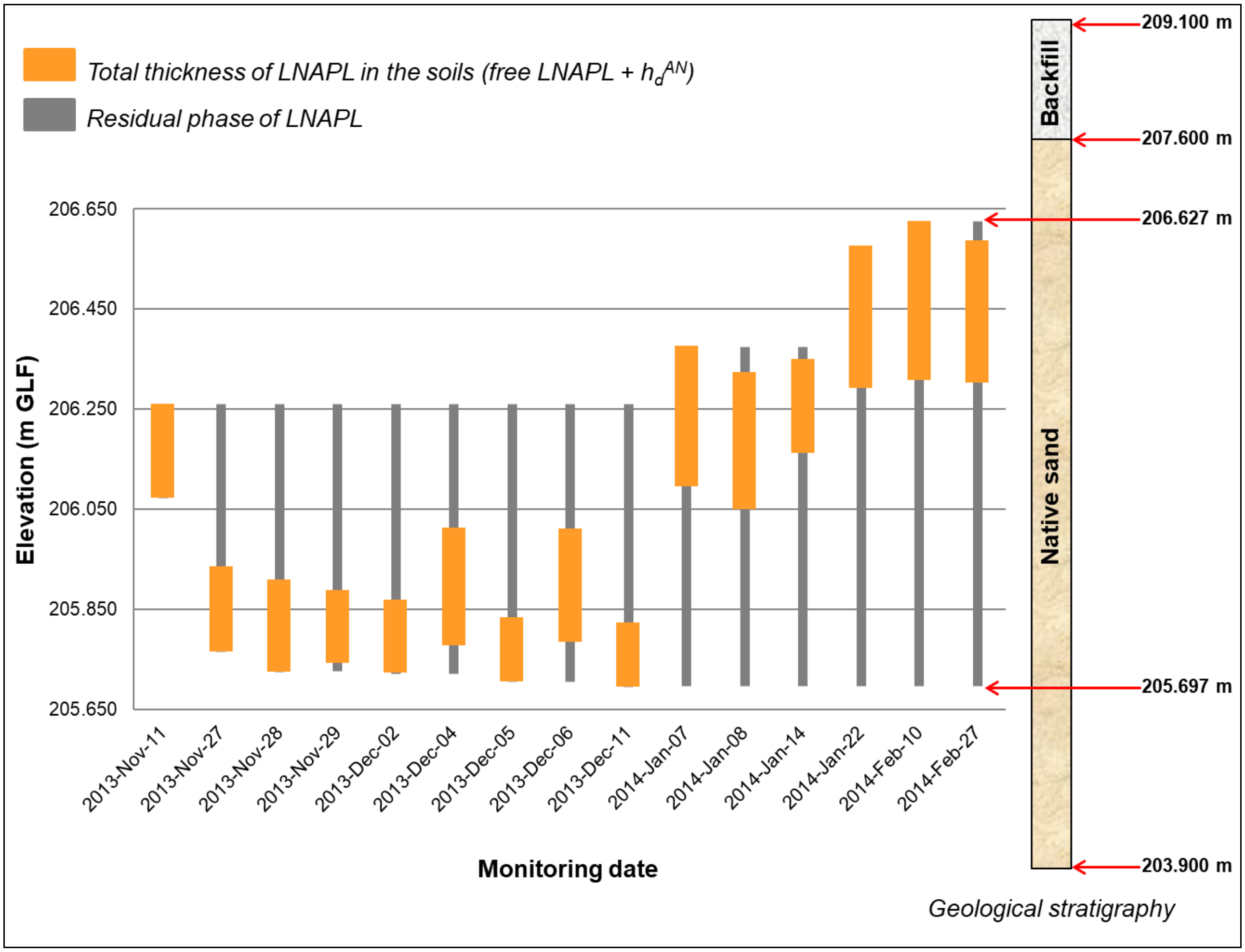

Figure 3. LNAPL phase localization following the water table fluctuations and evolution of the residual LNAPL phase

6 CONCLUSION

The analysis conducted in this study has allowed the determination of the total thickness of impacted soils and their location within the geological formation by considering the data collected as part of routine groundwater monitoring. This evaluation was determined by considering the presence of the free LNAPL in soils and also the soils potentially containing residual LNAPL. In addition, the water table fluctuations, which affect the location of the free LNAPL phase in soils and the determination of the soils potentially containing residual LNAPL, have been taken into account while assessing the total thickness of impacted soils. However, this assessment was determined by considering only the monitoring events conducted between November 11th of 2013 and February 27th of 2014. As these groundwater monitoring events were conducted on irregular periods, it is possible that other fluctuations that were not covered by the conducted groundwater monitoring events could then have occurred. Accordingly, further assessment of the total thickness of impacted soils would require documentation, both for water table fluctuations and for moving of the apparent LNAPL thickness in the observation well, from the initial time of spill. In addition, the presence of residual LNAPL in the soils has been attributed to all pathways where the free LNAPL has passed during its transport (from the top to bottom or from the bottom to top) considering a residual saturation of LNAPL in the soils surrounding the investigated observation well. To this end, further study on the residual saturation of LNAPL in soils would be very pertinent to this type of study.

The performed data processing in this case study shows that water table fluctuations affect the LNAPL location. Consequently, determining total thickness of impacted soils and its location within the geological formation would be a very useful element in the assessment of impacted soil volumes, if the performed processing is applied to all impacted observation wells located on the investigated site. Moreover, this evaluation is very pertinent for implementing in situ treatment systems, considering that it can make it possible to determine how deep the water table should be lowered, through pumping, in order that the impacted soils become located in an unsaturated zone and can then be subjected to an in situ treatment by, for example, ventilation or by thermal approach.

ACKNOWLEDGMENT

The author thanks the environmental consulting company *Sanexen services environnementaux inc*. that provided the data for this case study. The author thanks also the owner of the studied site that authorized publication of data for this case study, with the request that its identification be kept confidential. The author would like to thank two anonymous reviewers for their helpful comments and suggestions on improving this manuscript.

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