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Research article

LNAPL transmissivity as a remediation metric in complex sites under water table fluctuations

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A B S T R A C T

Water table fluctuations affect the recoverability of light non-aqueous phase liquid (LNAPL) petroleum hydrocarbons. LNAPL transmissivity (T_n) is being applied as an improved metric for LNAPL recoverability. In this paper, the applicability of T_n as a lagging and leading metric in unconsolidated aquifers under variable water table conditions was investigated. T_n values obtained through baildown testing and recovery data-based methods (skimming) were compared in three areas of a heterogeneous gasoline contaminated site in Western Australia. High-resolution characterisation methods were applied to account for differences in the stratigraphic profile and LNAPL distribution. The results showed a range of T_n from 0 m^2/day to 2.13 m^2/day, exhibiting a strong spatial and temporal variability. Additionally, observations indicated that T_n reductions may be more affected by the potentiometric surface elevation (Z_{aw}) than by the application of mass recovery technologies. These observations reflected limitations of T_n as a lagging metric and a Remedial Endpoint. On the other hand, the consistency and accuracy of T_n as a leading metric was affected by the subsurface conditions. For instance, the area with a larger vertical LNAPL distribution and higher LNAPL saturations found T_n to be less sensitive to changes in Z_{aw} than the other two areas during the skimming trials. T_n values from baildown and skimming tests were generally in a close agreement (less than a factor of 2 difference), although higher discrepancies (by a factor up to 7.3) were found, probably linked to a preferential migration pathway and Z_{aw}. Under stable Z_{aw}, T_n was found to be a relatively reliable metric. However, variable water table conditions affected T_n and caution should be exercised in such scenarios. Consequently, remediation practitioners, researchers and regulators should account for the nexus between T_n, LNAPL distribution, geological setting and temporal effects for a more efficient and sustainable management of complex contaminated sites.

1. Introduction

Petroleum hydrocarbons such as gasoline, diesel and jet fuel exist as light non-aqueous phase liquids (LNAPLs) in the subsurface and can pose risks to human health and the environment because of their potential and perceived mobility and toxicity (Tomlinson et al., 2017; Sookhak Lari et al., 2018). In-well LNAPL thickness (b_n) has been used as a common measure of potential LNAPL quantity, mobility and recoverability. However, b_n is strongly influenced by lithological strata, LNAPL properties and hydrogeologic conditions (ASTM, 2013). Consequently, the interpretation of b_n may require the application of models that account for capillary pressure-saturation relationships (Farr et al., 1990; Lenhard and Parker, 1990; Sleep et al., 2000; Charbeneau, 2007; Lenhard et al., 2017) and equilibrium in-well fluid levels should be representative of the fluid pressures in the formation.

To overcome limitations of use of b_n, LNAPL transmissivity (T_n), which is a measure of potential LNAPL recoverability, is being increasingly adopted as an important metric for the management of LNAPL contaminated sites. T_n is defined in an analogous way to

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groundwater transmissivity and can be estimated through baildown testing, manual skimming, recovery data-based methods (e.g. analysis of LNAPL skimming systems) or tracer tests (ASTM, 2013). Of the various techniques, baildown testing is the most commonly applied since it requires less resources than the other methods.

However, an in depth knowledge of the site conditions and the underlying multiphase physics is still essential to properly assess the system, since T_n has also been recently described as a complex parameter (Beckett and Huntley, 2015). Fig. 1 illustrates this complexity by showing the multiple interrelated sources of variability that affect T_n. The estimated T_n value depends on the applied methodology, test conditions, water table fluctuations as well as fluid and geological properties. These factors are usually related to T_n in a complex way: for instance hysteresis impacts the relationships between relative permeability, capillary pressure and saturation, determined by the geological and fluid properties. A 20% difference in T_n during imbibition or drainage periods in homogeneous porous media has been documented (Palmier et al., 2017). It is also crucial to assess if the LNAPL is under confined, unconfined or perched conditions since it affects the data analysis methodology. Many tools such as diagnostic gauge plots, core logging, HPT profiles, baildown testing and hydrostratigraphs are useful for this purpose (Kirkman et al., 2013).

Water table fluctuations may play a crucial role on LNAPL redistribution, its mobility and the partitioning into other phases and can affect the value of T_n by orders of magnitude (Beckett and Huntley, 2015). Two main mechanisms are behind the relationship between potentiometric surface elevation (Z_{aw}) changes and T_n. Firstly, the induced vertical displacement of LNAPL mass to zones with different intrinsic permeability. Secondly, the generation of immobile LNAPL, in particular the generation of entrapped and residual LNAPL when Z_{aw} increases or decreases. (Lenhard et al., 1993; Steffy et al., 1995; Chompusri et al., 2002). Hydrographs obtained from field sites usually show that Z_{aw} and T_n follow opposite trends (Beckett and Huntley, 2015), thus indicating the importance of entrapment phenomena in unconsolidated porous media. Recently, a model to predict subsurface LNAPL volumes and T_n after consideration of immobile LNAPL resulting from water table fluctuations in homogenous scenarios was presented (Lenhard et al., 2017; Lenhard et al., 2018). Heterogeneous systems require greater consideration.

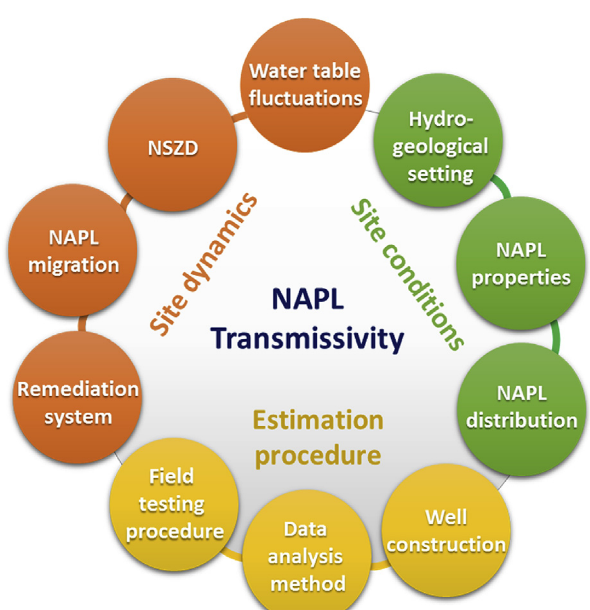

Fig. 1. Sources of variability contributing to the complex nature of T_n. NSZD stands for natural source zone depletion.

In spite of the aforementioned complexities, T_n is applied in the design, implementation and evaluation of remediation systems as both a leading and lagging metric (ASTM, 2013; Kirkman, 2013). A leading metric is an indicator of the potential future performance of a system. For instance, T_n is used to determine the start-up of a LNAPL mass recovery system or to gain insight into the expected LNAPL recovery rates. On the other hand, a lagging metric is an indicator of the past and current performance of a system. For instance, T_n is used to assess the progress of LNAPL mass recovery techniques and it is also used as a Remedial Endpoint to determine the shutdown of the recovery system. Other tools such as decline curve analysis (Sale and Applegate, 1997) can be used in conjunction with T_n. A T_n value of 0.009–0.07 m^2/day has been suggested as an endpoint criterion for hydraulic LNAPL recovery (ITRC, 2009). However, regardless of the specific remediation metric, approaches have been developed for evaluating alternative endpoints in lieu of regulatory standards (Harclerode et al., 2016) and adaptive management strategies have been adopted (Price et al., 2017) in the case of complex contaminated sites.

The objective of this paper is to assess the effects water table fluctuations may have on the estimation and applicability of T_n as a leading and lagging metric in heterogeneous unconsolidated aquifers. Although it has been stated that water table fluctuations may play a crucial role on T_n (Kirkman and Hawthorne, 2014; Beckett and Huntley, 2015), none of the existing field-based research papers (Nagaiah et al., 2015; Palmier et al., 2016; Pennington et al., 2016) have directly addressed the nexus between T_n, water table fluctuations, geological heterogeneity and complex NAPL distributions. This study encourages further research on this nexus and have a valuable impact on new regulatory frameworks and more efficient and sustainable contaminated site management strategies.

2. Materials and methods

2.1. Characteristics of the field site

The study area is comprised of an operating petrol station in Western Australia located within a residential-commercial zone. It occupies an area of 2750 m^2 where the topography is relatively flat. The local hydrogeology consists of a multi-layered unconsolidated aquifer system formed in a fluvial depositional environment. Discontinuous interbedded sands, silts and clays are present. In general, the stratigraphic profile consists of three main strata: a clayey silt layer approximately 0–4.5 m below the surface; a sandy layer (fine and coarse sand with up to 30% of silt and clay) approximately 4.5–8 m below the surface; and heavy clays approximately 8 m and deeper below the surface. A fining-upward sequence was observed in the sandy unit according to core logs.

The study area typically experiences annual water table fluctuations of 2–3 m. More specifically, Z_{aw} fluctuated between a maximum elevation of 59.6 m AHD (Australian Height Datum) and 56.2 m AHD during the 2014–2015 period while there was a fluctuation between 57.1 m AHD and 56.2 m AHD in the 2015–2016 cycle. Thus, the maximum Z_{aw} was 2.5 m higher in 2014 than in a particularly dry 2015, while the elevation minima were similar. The LNAPL was distributed mainly in the sandy material, being the transition point between confined and unconfined LNAPL conditions generally in the range of 56.7–56.8 m AHD. The gasoline release occurred in April 2013 at approximately the Z_{aw} minimum. The exact amount of released gasoline remains unknown. Physical and chemical measurements of the gasoline indicate it was relatively fresh with a measured mass density of 730 kg/m^3 and a viscosity between 4.1×10^{-4} $kg\,m^{-1}\,s^{-1}$ and 4.8×10^{-4} $kg\,m^{-1}\,s^{-1}$. Between 2014 and 2016, 85 monitoring points were installed including production (100-mm diameter) and monitoring wells (50-mm diameter), multi-level strings and vapor point wells. The well screened intervals were carefully chosen for the proper measurement of representative in-well fluid levels. Site characterisation included coring and direct-push profiling methods such as Hydraulic Profiling Tool (HPT) and Laser-Induced Fluorescence (LIF) at distances of less than 2 m away from installed wells.

Three areas (A, B and C), exhibiting differences in the vertical LNAPL distribution and the stratigraphic profile, were chosen to investigate the effect of water table fluctuations under different scenarios. The distance between the tested wells in areas A and B was 12 m. Area C was located 30 m away from the other two areas. The geological material at area C was generally finer textured than at the other two areas. Confined and unconfined LNAPL conditions were observed in the field site between 2014 and 2016. Lines of evidence such as diagnostic gauge plots, core logging, HPT profiles, baildown testing and hydrostratigraphs (Kirkman et al., 2013) suggested that all the T_n values presented in this study were measured during unconfined LNAPL conditions. Table 1 shows the monitoring network and the LNAPL hydrogeological conditions at the three research areas during the mass recovery testing periods.

2.2. Experimental procedure

Periodic measurements of $T_{n,BD}$ (T_n estimated through baildown testing) were obtained across the field site between 2015 and 2016. These measurements were taken under natural conditions to investigate two main aspects: (i) the spatial and temporal variability of T_n and (ii) the suitability of applying a single T_n value as a Remedial Endpoint in a dynamic system (results presented in section 3.1). In addition, LNAPL mass recovery methods were also tested to assess: (i) the applicability of T_n as a lagging metric monitoring the progress of the remediation system and (ii) the consistency of $T_{n,BD}$ as a leading metric in areas with similar $T_{n,BD}$ values, but different LNAPL distributions and geological materials (results presented in section 3.2). $T_{n,BD}$ and $T_{n,SK}$ (T_n estimated through skimming) were also compared to investigate the accuracy of $T_{n,BD}$ as a predictor of $T_{n,SK}$ (results presented in section 3.3).

In 2015, the LNAPL mass recovery trials were conducted sequentially in areas A and B. In area A, there was relatively constant water table conditions (water table elevation increased at a rate of 1 cm/week). In area B, there was a rising potentiometric surface (water table elevation increased at a rate of 5 cm/week). The 2016 trials were conducted in parallel during rising water table conditions (water table elevation increased at a rate of 7.5 cm/week at the beginning of the trial) at the three research areas.

In 2015, the skimming operations to recover LNAPL in areas A and B lasted two weeks. In 2016, the skimming operation at area B lasted four weeks. A 4-week sequential mass recovery trial took place at areas A and C. Besides skimming, the other applied LNAPL recovery techniques were water-enhanced recovery (dual pump inducing water table drawdown), vacuum-enhanced recovery and water- and vacuum-enhanced recovery, but their results are not included in this paper. LIF profiles and continuous soil cores were obtained before the start of the 2016 trials (mid-May 2016) to delineate the LNAPL vertical distribution. The equilibrium Z_{an} and the corresponding LNAPL drawdown used in the T_n analysis were estimated from the surrounding monitoring wells.

2.3. Measurements and calculations

To measure T_n in the field by the baildown testing procedure, initial Z_{an} (elevation of the air/LNAPL interface in a well) and Z_{nw} (elevation of the LNAPL/water interface in a well) measurements are collected. Consequently, a period of time is necessary after any active recovery operation to allow the in-well fluid levels to be representative of the fluid pressures in the formation. LNAPL is then removed from the well, which causes LNAPL to flow into the well from the surrounding porous media, including the filter pack. Both Z_{an} and Z_{nw} are measured as LNAPL flows into the well. Given the properties of the existing LNAPL and the equipment that was employed, baildown testing was apparently more reliable than the manual skimming method, even at relatively low in-well thicknesses. The data was analysed by using the modified Bouwer and Rice equation (Kirkman, 2013):

$$T_{n,BD} = \frac{r_e^2 \ln(R_{oi}/r_e)\ln\left(s_{n(0)}/s_{n(t)}\right)}{2(-J)t} \tag{1}$$

where:

$T_{n,BD} = T_n$ estimated through baildown testing [L^2/T];
R_{oi} = radius of influence for the NAPL phase [L];
r_e = effective well radius [L];
$s_{n(0)}$ = maximum induced drawdown [L];
$s_{n(t)}$ = LNAPL drawdown at time t [L];
t = elapsed time [T];
J = ratio of change in NAPL drawdown to change in NAPL thickness [−].

The terms L and T refer to units of length and time respectively. R_{oi} is the radius of influence for the LNAPL phase, also defined as radius of capture by other authors (Charbeneau, 2007). Thus, it is the radius of the area where a pressure gradient is generated. Under unconfined conditions, $s_{n(o)}$ is the distance between the equilibrium Z_{an} and the induced Z_{an} after the LNAPL bailing process. It should be noted that the assumption of vertical equilibrium is frequently not fully met under transient conditions in the field. In

Table 1
Monitoring network and LNAPL hydrogeological conditions during the mass recovery trials at the three research areas. Numbers in parenthesis indicate the distance from recovery wells.

Research Area	Recovery Well	Observation Wells	LIF Profiles	HPT Profiles	NAPL Conditions
A	PB29	MP50 (1.5 m) MP77 (1 m)	LIF43 (1 m) LIF47 (1.5 m)	HPT73 (1.5 m)	Unconfined
B	PB27	PB09 (2.5 m)	LIF 51 (1.5 m) LIF52 (1 m) LIF53 (2 m)	HPT74 (1 m)	Unconfined
C	PB40	PB11 (4 m) MP44 (1.5 m) MP78 (1 m)	LIF57 (2 m) LIF68 (2 m)	HPT59 (3 m) HPT60 (2 m) HPT62 (2 m)	Unconfined

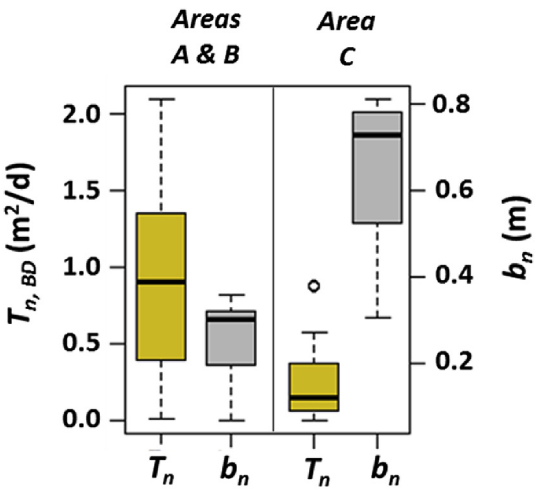

Fig. 2. Distribution of T_n and b_n values across the site in the years of research.

addition, some of the theoretical assumptions in the Bouwer and Rice approach (Bouwer and Rice, 1976) are not necessarily met for multiphase systems and T_n analysis (Batu, 2012). However, several authors have defended this methodology claiming that is robust enough under both field and laboratory conditions (Charbeneau et al., 2013; Palmier et al., 2017), with different analytical solutions presenting a good correlation at field scale under unconfined conditions (Palmier et al., 2016).

Regarding the data collection and analysis procedure during mass recovery operations, LNAPL recovery rates were systematically measured and the corresponding LNAPL drawdowns estimated. The modified Thiem equation (Charbeneau, 2007) was used for the calculation of $T_{n,SK}$:

$$T_{n,SK} = \frac{Q_n \ln\left(\frac{R_{oi}}{r_w}\right)}{2\pi s_n} \tag{2}$$

where:

$T_{n,SK} = T_n$ estimated through skimming [L^2/T];
$Q_n =$ the time-weighted mean of the measured LNAPL recovery rates [L^3/T];
$s_n =$ the geometric mean of the estimated LNAPL drawdowns [L];
$r_w =$ well radius [L].

The value of ln (R_{oi}/r_w) was assumed to be equal to 4.6 introducing little error according to the literature (ASTM, 2013). The estimated $T_{n,BD}$ value may not compare well with $T_{n,SK}$ because of the analysis procedure and temporal and spatial scale dissimilarities. Such discrepancies have been documented when comparing slug tests and pumping tests in groundwater systems (Butler and Healey, 1998). The spatial scale of the selected methods is determined by their radius of capture, typically larger for coarser-grained sediments (Beckett and Huntley, 1998).

3. Results and discussion

3.1. Variability in LNAPL transmissivity under natural water table fluctuations

Fig. 2 depicts the distribution of the T_n and b_n values obtained through the field site monitoring network over two years. $T_{n,BD}$ ranged from practically 0 m^2/day to 2.13 m^2/day across the site. Area C had the lowest $T_{n,BD}$ values (0.07–0.58 m^2/day) among the three areas since 2015 (maximum values of 2.13 m^2/day at research area A and 1.38 m^2/day at research area B), despite higher LNAPL saturations and b_n. The low intrinsic permeability at area C is a key factor for the lower T_n values. A lack of correlation between T_n and b_n was consistently observed at the field site, as shown in Fig. 2. This behaviour has also been documented in the literature (Palmier et al., 2016). However, a positive relationship between these two parameters was found at specific wells tested during unconfined LNAPL conditions, consistent with the multiphase theory (Lenhard et al., 2017), although the goodness of fit of the linear regression models (R^2) were between 0.35 and 0.76 (data not shown). T_n exhibited a strong spatial variability. For instance, no LNAPL was present in wells located less than 2 m away from others with the highest T_n values.

Fig. 3 illustrates the site hydrograph during the study period. All the depicted $T_{n,BD}$ values corresponded to periods of unconfined LNAPL conditions. Between 2015 and 2016, a reduction in T_n during rising water table conditions was generally observed. This behaviour was related to two different processes: (i) less mobile LNAPL because of LNAPL entrapment by water and (ii) upward LNAPL displacement into porous media with a lower intrinsic permeability. $T_{n,BD}$ became practically negligible under the highest measured Z_{aw} values (data not shown). The potential disconnection between the LNAPL in the well and the formation under these conditions (confined or near-confined LNAPL according to several lines of evidence) could be an additional reason behind this behaviour.

Differences in $T_{n,BD}$ at similar Z_{aw} values in 2015 compared to 2016 (54% $T_{n,BD}$ decrease at area B) may reflect hysteresis, natural

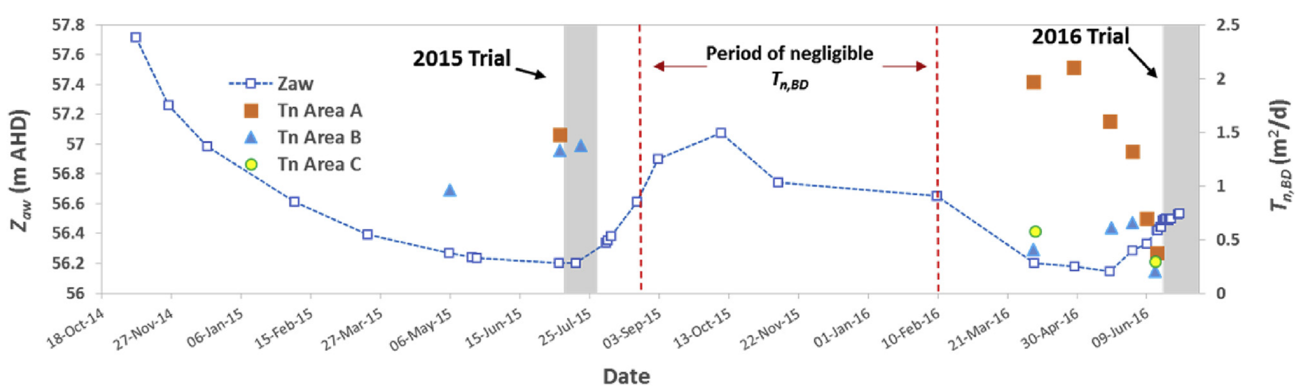

Fig. 3. Contaminated site hydrograph along with $T_{n,BD}$ values at the three research areas. Grey columns indicate the time periods of recovery applications in 2015 and 2016.

LNAPL depletion or mass migration within the LNAPL body. Another observation supporting the strong influence of Z_{aw} on T_n was that an increase of 25 cm in Z_{aw} resulted in a $T_{n,BD}$ decrease from 2.13 to 0.37 m^2/d in area A (which exhibited the lowest LNAPL mobile intervals according to LIF and core logs). These changes in T_n could explain differences of up to one order of magnitude estimated from initial baildown testing and long-term methods such as tracer tests (Pennington et al., 2016). Note that the redistribution of LNAPL can be favoured by its relatively low density and viscosity, since these physical properties affect LNAPL relative permeability and LNAPL residual and entrapment phenomena.

3.2. Variability in LNAPL transmissivity during skimming

LNAPL saturations obtained from extracted cores (MP50 in area A, MP44 in area C) before the 2016 mass recovery trial (May 2016), as well as HPT and LIF logs from surrounding direct-push locations, are presented in Fig. 4. Cores (MP77 in area A, MP78 in area C) were collected after the trial (August 2016) to assess the LNAPL redistribution and mass changes. The highest LNAPL saturations were found at area C, where the material was finer grained. During the skimming trials, soil coring, HPT and LIF profiles suggested that the mobile LNAPL interval was mainly located in silty sands in area C. In addition, there were greater differences between the HPT logs obtained in area C compared to areas A and B. This can be seen from the three different HPT logs corresponding to this area in Fig. 4. HPT logs were found to be a relatively good indication of the aquifer thicknesses and the transition points between different strata.

In areas A and B, the mobile LNAPL interval was located in poorly graded sandy material. Data for area B is not shown in Fig. 4 because of the similarities with geological material and T_n evolution in area A. A notable feature in area A was the distinct and very high LIF signals within an interval of just 12 cm (Fig. 4a), where a slightly coarser material was identified. The highest LIF signals were present in area A which had lower LNAPL saturations than in areas B and C (Fig. 4b). Because the LIF signal is also influenced by the geological medium (Lu et al., 2014), LIF can be an interesting tool to delineate such transmissive intervals. The thin layer acted as a preferential migration pathway limiting vertical displacement of LNAPL due to capillary contrasts, as indicated by the minimal LNAPL redistribution at the end of the recovery trial. Different lines of evidence (such as the interpretation of baildown tests and diagnostic gauge plots) suggested unconfined LNAPL conditions this period of time.

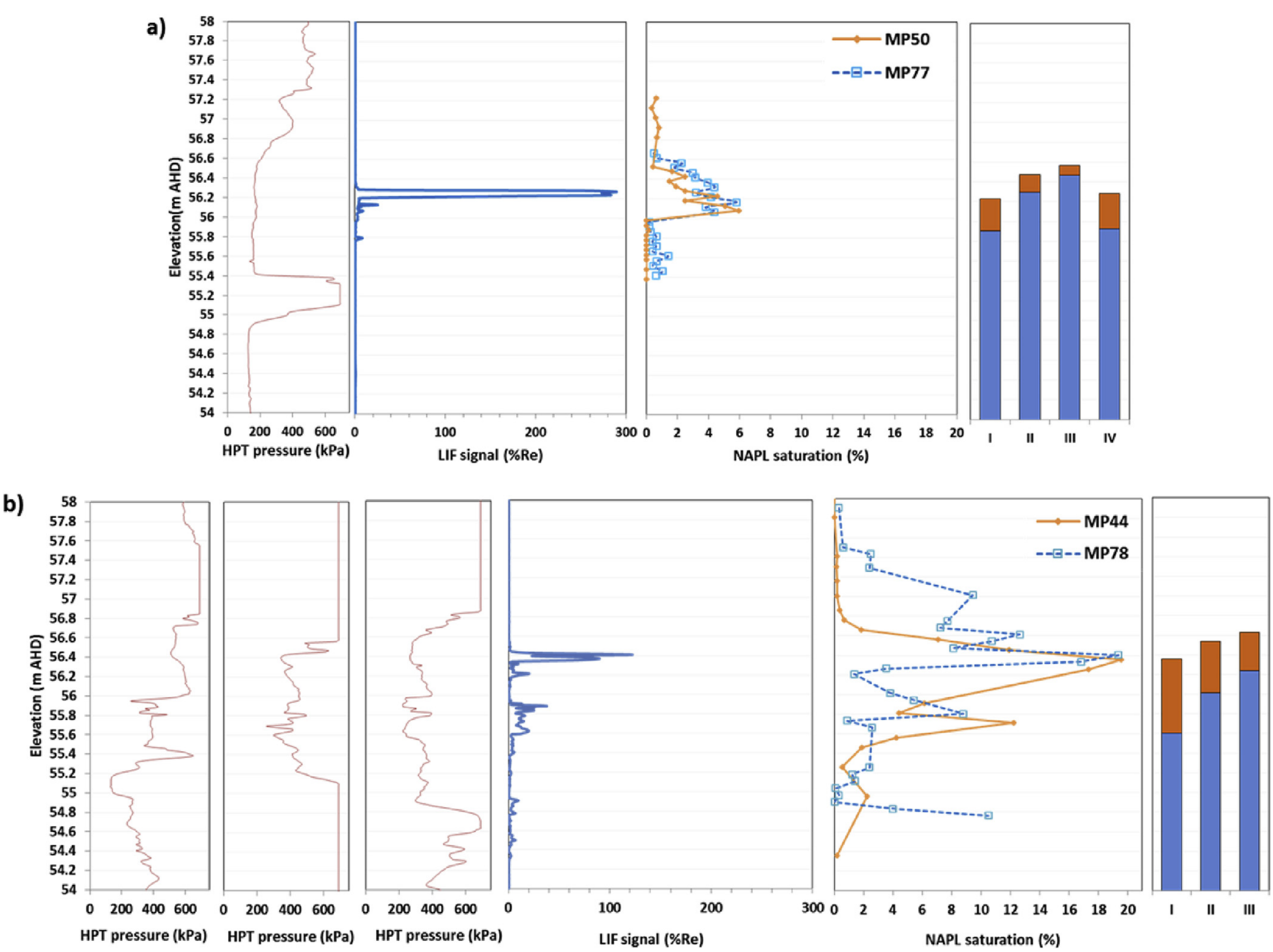

Fig. 4. a) HPT73 and LIF43 profiles along with LNAPL saturations (MP50, MP77) and fluid levels (where the orange interval corresponds to b_n and the blue interval is the water column at PB29 well) from area A and b) HPT59, HPT60, HPT62 and LIF57 profiles along with LNAPL saturations (MP44, MP78) and fluid levels (PB40 well) from area C. Four different fluid elevations are illustrated: **I** refers to fluid levels the day of core sampling (late May 2016), **II** shows the fluid levels the day before the 4-week sequential free recovery trial (mid-June 2016), **III** presents fluid levels just after the end of the recovery trial (early July 2016) and, finally, **IV** refers to the fluid levels just before the 2015 trial (early July 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In addition, Fig. 4 presents four periods when in-well fluid levels (**I**, **II**, **III**, **IV**) were measured. Times **I** and **IV** were at the lowest monitored Z_{aw} during the years 2015–2016 with small differences in Z_{an} and Z_{nw}. The LNAPL saturation profiles shown in Fig. 4 correspond to time **I**. A different LNAPL distribution, exhibiting lower NAPL saturation values is expected at time **II**, as it has been previously documented in the case of a gasoline contaminated sandy aquifer with a rising potentiometric surface (Steffy et al., 1995). At the beginning of the mass recovery trials, higher values of $T_{n,BD}$ were measured in July 2015 (1.48 m^2/d) compared to June 2016 (0.37 m^2/d). In 2015, measurements were taken under low water table conditions, whereas in 2016 the water table was 20–25 cm higher. It should be noted that LNAPL recovery was negligible in all the research areas at the end of the 2016 trial.

Fig. 5 illustrates changes in $T_{n,SK}$ with Z_{aw} during the first week of the skimming trial in 2016. During the first 5-cm rise in Z_{aw} (56.43–56.48 m AHD), $T_{n,SK}$ was near constant in area C, in contrast to areas A and B. One important factor was that the LNAPL saturations in area C were higher. How LNAPL saturation is affected by Z_{aw} changes depends on the capillary pressure-saturation relationship. Moreover, the LNAPL mobile interval was larger for area C. In relation to this, b_n (4.5 times larger at area C than at area A) was reduced by 7% in area C, but it decreased by 15% in area A during this period of time. Thus, entrapment phenomena and vertical displacement had a more significant influence in area A at this time. It should also be noticed that the lowest $T_{n,SK}$ values were estimated for area C. Later measurements showed $T_{n,SK}$ approaching zero under constant water table elevations in area C due to LNAPL mass recovery through skimming in the surrounding subsurface. Low $T_{n,BD}$ measured values in surrounding wells was another indication of the low LNAPL mobility in this area.

Fig. 6 presents changes in $T_{n,BD}$ before and during the skimming trial in area A in 2016. It gives an indication of the influence of the skimming operations compared to the behaviour of $T_{n,BD}$ under natural water table fluctuations. It can be inferred that T_n estimates trend with water table elevation changes, while the effect of LNAPL mass removal during skimming operations was not apparent. Consequently, at this time water table rise seems to have played a greater role in the temporal reduction of T_n than mass recovery. This is supported by observations of relatively constant T_n during periods of stable water table conditions. Further, T_n did not change under constant Z_{aw} at area A during the 2015 trial, whereas the effect of an increasing Z_{aw} had a negative impact on T_n at area B (Gatsios et al., 2016). The behaviour shown in Fig. 6 indicated that the assessment of the performance of a remediation system through T_n could be misleading. For instance, other authors acknowledged the effectiveness of a LNAPL recovery system after observing a T_n decrease of 47% after 18 months of recovery (Palmier et al., 2016). However, Fig. 3 shows a 54% $T_{n,BD}$ reduction under natural conditions without remediation operations at area B between 2015 and 2016.

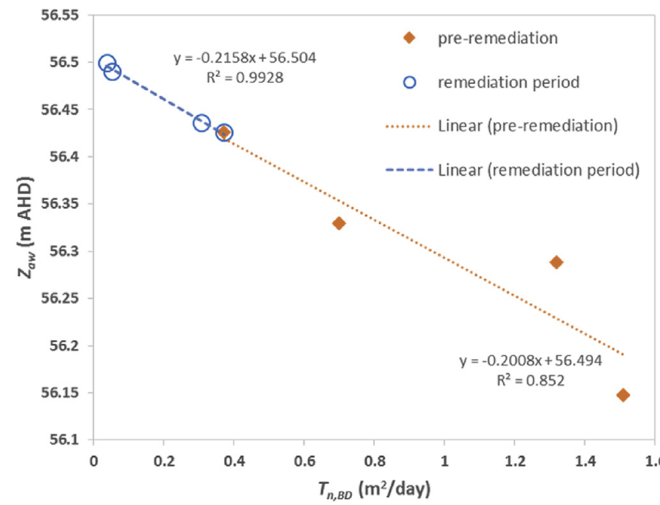

Fig. 6. $T_{n,\,BD}$ values before and during the 2016 skimming trial at area A.

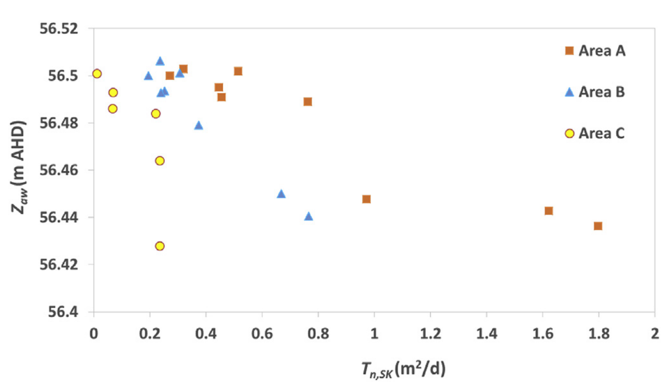

Fig. 5. Profiles of $T_{n,\,SK}$ and Z_{aw} at areas A, B, and C during the first week of the 2016 skimming trials.

3.3. *Comparison between LNAPL transmissivity estimated through baildown and mass recovery testing methods*

Fig. 7 shows a comparison of T_n values estimated from baildown testing and skimming for areas A and C during the recovery trials in 2015 and 2016. In general, for the 2015 trial in area A and the 2016 trial in area C, there was relatively close agreement between $T_{n,BD}$ and $T_{n,SK}$ with differences within a factor of 2. This difference is considered reasonable (ASTM, 2013) and is consistent with what has been documented in the literature (Nagaiah et al., 2015). More specifically, differences between $T_{n,BD}$ and $T_{n,SK}$ were relatively small under stable water table conditions. However, larger differences by a factor up to 7.3 were found in area A during the 2016 LNAPL mass recovery trial. This occurred on a period of rising water table conditions. Improved correlation between $T_{n,SK}$ and $T_{n,BD}$ in area C over this similar period is thought to be due to the finer grained material compared to area A as this strongly influences the radius of capture.

Fig. 8 provides further insight into the relationship between the $T_{n,SK}/T_{n,BD}$ ratio and Z_{aw} in areas A and C. The figure includes periods when skimming and water-enhanced skimming recovery methods were employed. As the $T_{n,SK}/T_{n,BD}$ ratio approaches unity, baildown testing estimations could be considered as good predictors of T_n and recoverability for mass recovery applications. Fig. 8 shows that the difference between both T_n estimation methods may be a function of Z_{aw} as well as other factors. Note that for area A, the previously cited difference by a factor of 7.3 corresponds with the highest Z_{aw}.

As depicted in Fig. 4a, the LNAPL distribution in area A largely occurred within a thin depth interval whereas a thicker LNAPL vertical distribution with higher saturations existed in area C. Therefore, the remarkably high $T_{n,SK}/T_{n,BD}$ ratio at high Z_{aw} is likely due to the coupled effect of the differences in the radius of capture between the two estimation methods and the low LNAPL saturations predominantly constrained to a thin layer. In such a scenario, the transient conditions due to water table fluctuations may have an enhanced effect on the relation between the in-well fluid elevations and the LNAPL in the formation. The baildown testing

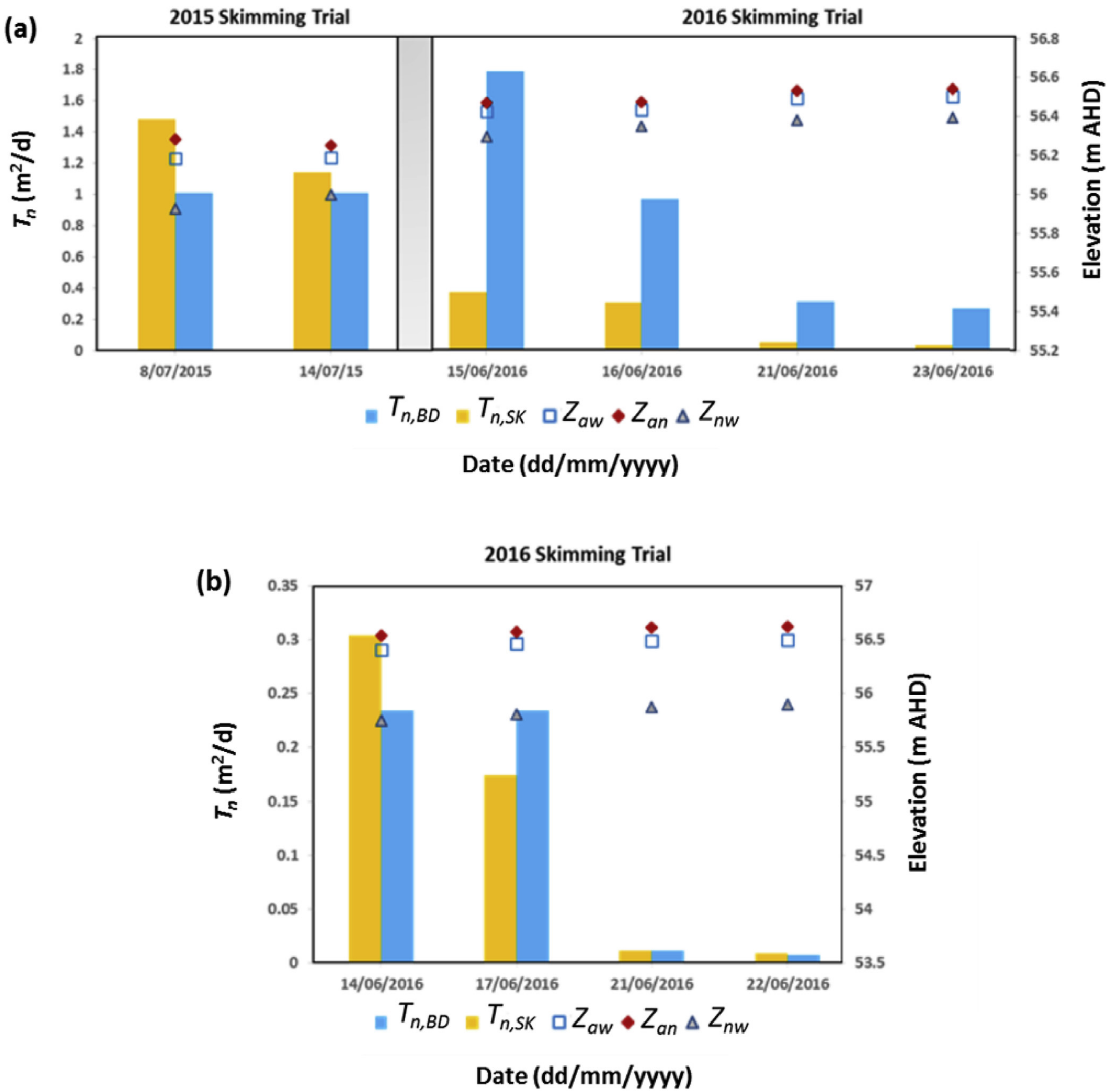

Fig. 7. Comparison of T_n values from baildown testing and skimming along with fluid elevations in (**a**) area A (2015 and 2016 trials) and (**b**) area C (2016 trial).

estimates were more afftected by the rising water table than the effects of skimming system; this can be inferred from the decreasing $T_{n,SK}$ with an increasing $T_{n,SK}/T_{n,BD}$ ratio. Thus, the accuracy of $T_{n,BD}$ as a predictor of $T_{n,SK}$ may be compromised when significant water table fluctuations exist.

4. Conclusions

In the present study, the applicability of T_n as a metric in heterogeneous systems with water table fluctuations was investigated. Water table fluctuations strongly influenced estimates of T_n and should always be taken into consideration by remediation practitioners, researchers and regulators. The findings of this research encourage the use of T_n as a metric for the management of LNAPL contaminated sites, but emphasises the importance of an accurate conceptual site model.

Under constant water table conditions, T_n was found to be a relatively reliable metric for the management of saturation-based risks in LNAPL contaminated sites, albeit exhibiting a strong spatial dependency. $T_{n,BD}$ and $T_{n,SK}$ were usually in a close agreement. Consequently, $T_{n,BD}$ is helpful in order to decide the appropriateness of establishing a new mass recovery system. In addition, the stable T_n behaviour favours the suitability of T_n as a leading metric.

In contrast, variable water table conditions may affect the evolution of T_n in such a way that its applicability as a metric may be questionable without a deep understanding of the site conditions. Examples supporting this statement were presented throughout

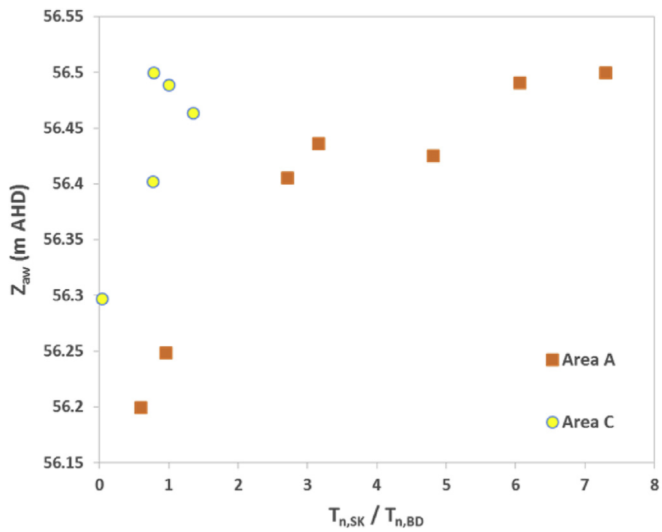

Fig. 8. Profile of Z_{aw} values along with $T_{n,SK}/T_{n,BD}$ ratio values at areas A and C during the skimming and water-enhanced skimming trials in 2016.

the results of this research and include:

(i) periods of high T_n may exist after periods of negligible LNAPL mobility on a cyclic basis. Thus, regulatory limits like the fixed endpoint criterion proposed by ITRC (ITRC, 2009) should be used with caution and preferably under low water table conditions (still depending on the relative importance of entrapment and the implications of vertical displacement). The results of this study encourage the application of periodic baildown testing as part of a broader adaptive management strategy;

(ii) $T_{n,BD}$ may potentially be more sensitive to water table changes than to LNAPL mass depletion through skimming. As a consequence, T_n is not necessarily representing the remediation performance of the mass recovery system only. It also comprises the coupled effects produced by the variable water table as well as the potential migration and natural losses occurring within the NAPL body. For instance, in this research the decrease in $T_{n,BD}$ due to natural conditions without remediation operations was similar to that presented in the literature after 18 months of LNAPL recovery (Palmier et al., 2016). Consequently, the understanding of these effects is essential in order to select the most appropriate remediation technology, such as cases where mass recovery techniques should be replaced by monitored natural attenuation strategies;

(iii) the effect of water table fluctuations is related to the geological setting and the NAPL distribution. Accordingly, areas with similar initial $T_{n,BD}$ values may exhibit a clearly different evolution with time. During this research study, T_n was found to be less sensitive to Z_{aw} when thicker vertical LNAPL distributions and higher saturations were present. As a consequence, the application of T_n as a leading metric is compromised without a deep knowledge of the conditions in the subsurface. Understanding the stratigraphy and the depositional environment may help to understand the influence of LNAPL vertical displacement and the influence of entrapment phenomena on T_n;

(iv) furthermore, Z_{aw} may affect the difference between estimates of $T_{n,SK}$ and $T_{n,BD}$. The magnitude of this difference may be related to the geological setting and LNAPL distribution. In this study, the largest differences were related to a thin vertical LNAPL distribution linked to a preferential migration pathway where restrictions to vertical LNAPL movement were measured. For this reason, some errors may arise from the usage of $T_{n,BD}$ as a start-up metric under these conditions.

In conclusion, both the geological setting and the LNAPL distribution have an effect on the behaviour of T_n, magnified in the case of variable water table conditions. Thus, a thorough characterisation of the area surrounding the remediation well improves T_n as a metric. In addition, periodic baildown testing assists in the assessment of T_n variability with time. Periodic measurements of $T_{n,BD}$ would also provide further insight into the comparisons between baildown and long-term testing methods like those already documented in the literature (Pennington et al., 2016). Further research under controlled environments is suggested to continue elucidating the complex interrelation between T_n, NAPL properties, NAPL distribution, geological setting and temporal effects including variable Z_{aw}, natural source zone depletion, NAPL migration and NAPL depletion through mass recovery methods.

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