Groundwater
Monitoring&Remediation

Comparison of Oil Transmissivity Methods Using Bail-Down Test Data

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Abstract

This paper evaluates the results from three methods commonly used to estimate oil transmissivity: the modified Cooper solution (Beckett and Lyverse 2002), the modified Bouwer and Rice method (Kirkman 2013), and the modified Jacob and Lohman method (Huntley 2000). Determining the validity of oil transmissivity values is important (e.g., when used in extraction system design and operation) and not straightforward as these methods are based on different assumptions and boundary conditions and introduce different simplifying assumptions to allow for estimating oil drawdown. Data from 289 bail-down tests performed during an oil remediation project were used in this evaluation. Analysis of these tests produced realistic transmissivity values and good correlation between these three methods, giving the authors confidence in the oil transmissivity values as this correlation is reflected across a significant number of data sets. Secondly, the nature of oil and water recharge to the wells interpreted from Kirkman's J-ratio values largely validates the Huntley (2000) simplifying assumption that the potentiometric surface will be relatively constant during the test, allowing the use of the modified Bouwer and Rice method. Finally, the impact of oil extraction on measured oil thickness and estimated oil transmissivity was also assessed. The study showed a clear general decrease in both measured oil thicknesses and estimated oil transmissivity during the oil recovery project. However, measured oil thickness and estimated oil transmissivity are not clearly correlated, and, as a consequence, the range of decrease in one parameter does not allow any prediction of the range of decrease in the second parameter.

Introduction

The bail-down test and the closely related slug test are commonly used in single wells for in situ estimation of hydraulic conductivity in a single-phase (water only) system. These techniques became prevalent for several reasons, including the need for less equipment and manpower compared to performing a typical pumping test, the relatively rapid pace in completing the field work, the perceived ease of data analysis and the small amount of water that is removed from the well (Hyder and Butler 1995). The error introduced by the classical analytical interpretation of slug test analysis methods (Cooper et al. 1967; Bouwer and Rice 1976) was studied by others (Campbell et al. 1990; Brown et al. 1995; Hyder and Butler 1995; Halford et al. 2006) for tests in single-phase systems.

Within the past 35 years, bail-down tests have also been performed in the environmental industry to gather information about site-specific subsurface conditions in a two-phase (water and oil) system (Yaniga and Demko 1983). In this paper, the term "oil" is used when referring to a light non-aqueous phase liquid with a measurable thickness found in wells above the groundwater. Specifically, the bail-down test has been used to assess the oil mobility in porous media. Oil transmissivity is typically determined using modified analytical solutions originally developed for a water-only system. These modified solutions for a two-phase system, derived from the Bouwer and Rice approach (Lundy and Zimmerman 1996; Huntley 2000) and from the Cooper solution (Beckett and Lyverse 2002), are based on the boundary conditions and assumptions of the original water-only system solutions. However, boundary conditions or critical assumptions, such as initial drawdown being relatively small when compared with the aquifer thickness, do not consistently occur and are not consistently followed during the bail-down test in the two-phase systems.

In addition, Lundy and Zimmerman (1996) and Huntley (2000) introduced different important simplifying assumptions in their modified Bouwer and Rice solutions to allow calculation of the drawdowns. The validity of the analytical solutions for a bail-down test in a two-phase system and the range of error introduced by these different approaches are still being discussed (Batu 2012, 2013; Charbeneau et al. 2013). Kolhatkar et al. (1999) studied and showed the consistency of the oil transmissivity values determined by the analytical solutions with the values measured on undisturbed soil cores. Others compared the results from different analytical solutions working with data from only two to three

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wells (Krol 1995; Huntley 2000; Charbeneau 2012). These studies suggest that, while none or only a part of the boundary conditions or the assumptions are valid for the test, the comparison between the three methods of analysis is good, and one can be assured that the calculated oil transmissivity value is representative of field conditions near the test well (Charbeneau et al. 2013). However, there is no large-scale evaluation of the consistency of the oil transmissivity values estimated from these different analytical solutions largely used by practitioners to assess oil mobility in porous media.

The objectives of this paper are thus to: (1) assess, using a data set of 289 bail-down tests, the validity of the oil transmissivity values obtained from three commonly used methods of interpretation based on the boundary conditions and assumptions used to develop the water-only system solutions, (2) verify whether the simplifying assumptions proposed by Lundy and Zimmerman (1996) and Huntley (2000) to calculate the drawdown are consistently met for these site-specific conditions and oil characteristics, and (3) assess the relationship between temporal changes in oil thickness and transmissivity during long-term oil extraction.

The paper is organized as follows. Section *Oil Bail-down Test Theory* summarizes the main theories for interpretation of bail-down test in single and two-phase systems. Section *Material and Methods* presents the field case study including (1) the site-specific conditions, the oil physical properties and the oil collection system and (2) a description of the bail-down test protocol. In Section *Results*, the rates of oil and water recharge to the wells are evaluated to test the validity of the Huntley (2000) and Lundy and Zimmerman (1996) simplifying assumptions under these site-specific conditions. Oil transmissivity values obtained from three different methods are then compared to assess whether the calculated values are representative of field conditions near the test wells. Then, the changes in oil thickness and oil transmissivity values during the first years of the remediation project are evaluated to assess the ongoing remediation efficiency. Finally, Section *Summary and Discussion* expands the conclusions from Section *Results* on the data quality from field bail-down tests, the nature of the well recharge for these site-specific conditions, the validity of the oil transmissivity values obtained from the modified Bouwer and Rice solution (Huntley 2000), the modified Cooper solution (Beckett and Lyverse 2002) and the modified Jacob and Lohman solution (Huntley 2000), and the temporal variations in oil thickness and transmissivity.

Oil Bail-Down Test Theory

Analytical solutions to assess oil transmissivity were developed around 2000 and were based on commonly used bail-down tests. Several authors suggested applying (1) traditional slug test analyses (Cooper et al. 1967; Bouwer and Rice 1976) or (2) modified pumping test theory (Jacob and Lohman 1952) to interpret bail-down test measurements in a well where oil was present.

Figure 1 presents the geometry and the symbols of a bail-down test performed in a water-only system.

For a water-only system, the solutions are based on different boundary conditions and assumptions which are critical for the validity of the analysis. The Bouwer and Rice solution (Bouwer and Rice 1976) is based on the Thiem equation for steady-state radial flow to a well, and therefore, the drawdown initiated by the bail-down test needs to be negligible compared to the aquifer thickness. This solution applies to bail-down tests in unconfined aquifers, but the authors suggested that the solution could be applied to confined or unconfined aquifers with a fully or partially penetrating well. On the other hand, the Cooper solutions (Cooper and Jacob 1946; Cooper et al. 1967) apply to unsteady flow with constant discharge and variable drawdown (or with variable discharge and constant drawdown) to a fully penetrating well in a confined aquifer. In this approach, the bail-down test is assumed to be a series of steady states.

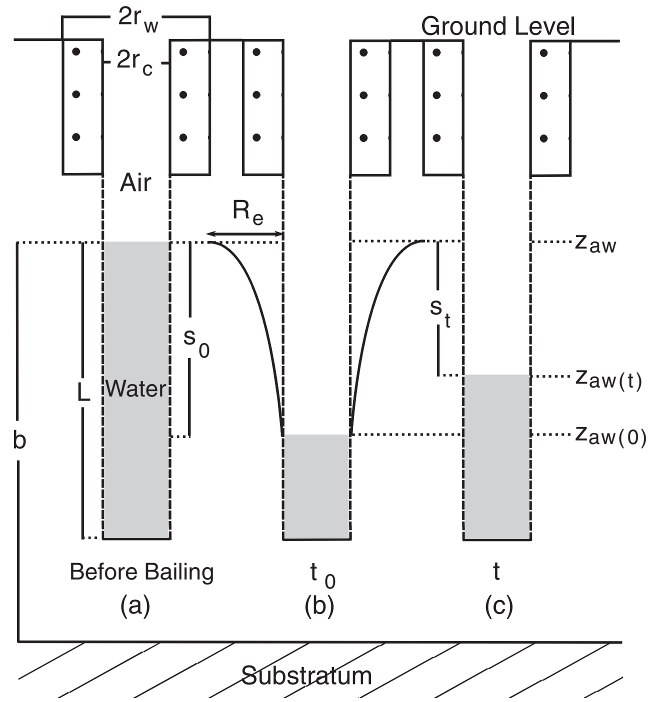


Figure 1. Geometry of partially penetrating wells in a water system (a) before water bailing, (b) at time t_0, and (c) at time t_1 after water bailing.

For an oil/water system, different solutions are presented using the symbols as defined on Figure 2.

The commonly used solutions (Table 1) are the modified Bouwer and Rice approaches (Lundy and Zimmerman 1996; Huntley 2000), the modified Cooper solution (Beckett and Lyverse 2002), and the modified Jacob and Lohman solution (Huntley 2000).

The solutions that were validated for a water-only system are often directly applied to an oil/water system keeping the same boundary conditions. In addition, authors (Lundy and Zimmerman 1996; Huntley 2000) introduced simplifying assumptions to find a solution for drawdown calculation (Table 1). The Lundy and Zimmerman method assumes that no water enters the well after the oil is removed. This constraint assumes the oil/water interface is not moving during the test which is quite uncommon and not expected. Huntley (2000) makes the assumption that the water transmissivity is for a majority of conditions much greater than

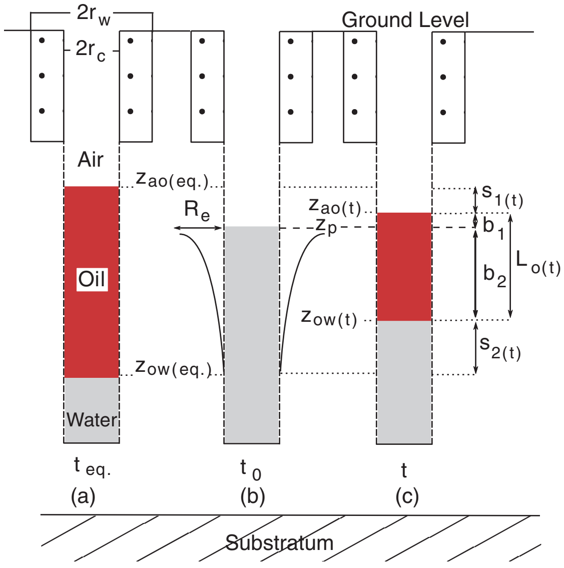


Figure 2. Geometry and symbols of partially penetrating wells in an oil/water system (a) at the equilibrium conditions, (b) at time t_0, and (c) at time t_1 after oil bailing.

the oil transmissivity and so the total potentiometric surface remains almost constant during the test. Thus, for a given data set, these two solutions produce significantly different results (Lundy 2002).

These approaches limit the application of the modified Bouwer and Rice method to the bail-down tests which meet the Huntley or the Lundy and Zimmerman assumption. In reality, neither of the boundary conditions specified by these authors are consistently met in all bail-down tests. More recently, Kirkman (2013) proposed a calculation methodology (Equation 5), where the potentiometric surface or oil/water interface is not required to be constant. This method makes the modified Bouwer and Rice approach applicable to a wider range of bail-down tests.

$$T_o = \frac{r_c^2 \ln\left(R_e/r_w\right)}{-2J}\frac{1}{t}\ln\left(\frac{s_{1(0)}}{s_{1(t)}}\right)5 \tag{5}$$

where J is the J-ratio defined by:

$$J = \frac{\Delta s_n}{\Delta b_n} \tag{6}$$

In Equations 5 and 6, T_o is the oil transmissivity, r_c is the well casing radius, R_e is the effective radius of the well, r_w is the borehole radius, $s_{1(0)}$ is the oil drawdown at t_0, $s_{1(t)}$ is the oil drawdown at t, s_n is the oil drawdown and b_n is the oil thickness measured in the well.

Using this approach, it is assumed that the ratio of oil head variation to oil thickness variation is constant; a set of data is therefore suitable for analysis if the plot of oil drawdown versus oil thickness can be fitted to a straight line, with the slope of that line being the J-ratio.

An objective of this paper is to test the validity of the above mentioned assumptions by comparing the different solutions over a significant number of tests.

Material and Methods

The studied site is a manufacturing facility which started production in 1973 using several types of oil. The site is located on the alluvial plain of the Garonne River in France. The local shallow strata are composed of 12 to 18 m of Pleistocene sediments, mainly gravel and sand, over a thick Tertiary marl layer (Figure 3).

Table 1

Summary of Analytical Solutions for Bail-Down Tests in an Oil/Water System

Authors	Assumptions/Boundary Conditions	Analytical Solutions to Assess the Hydraulic Transmissivity
Bouwer and Rice-modified solution. Lundy and Zimmerman 1996	• Changes in oil thickness are assumed to represent changes in oil head. • No groundwater flow to the well is assumed after the oil is bailed. • The depth to the water is constant during the test.	$T_o = \frac{r_c^2 \ln\left(R_e/r_w\right)}{2}\frac{1}{t}\ln\frac{s_{1(0)}}{s_{1(t)}}$ (1)
Bouwer and Rice-modified solution. Huntley 2000	• Changes in the elevation of the oil/air interface in the well represent changes in oil head. • The groundwater transmissivity is much greater than the oil transmissivity. • The groundwater potentiometric head is constant during the test.	$T_o = \frac{r_c^2\left(\frac{1}{1-\rho_o}\right)\ln\left(R_e/r_w\right)}{2}\frac{1}{t}\ln\left(\frac{s_{1(0)}}{s_{1(t)}}\right)$ (2)
Cooper et al.-modified solution. Beckett and Lyverse 2002	• Confined aquifer with fully penetrating well. • Resulting oil transmissivity values need to be multiplied by the oil density correction factor $(1/1-\rho_o)$.	$\frac{z_{ao(t)}}{z_{ao(0)}} = 8\alpha/\pi^2\int_0^\infty e^{-\beta u^2/\alpha}du/\left(u\Delta(u)\right)$ (3) where $\alpha = r_c^2 S/r_w^2$ and $\beta = T_o t/r_w^2$
Jacob and Lohman-modified solution. Huntley 2000	• Oil recovery is assumed to be slow enough to consider a pseudo steady-state condition.	$\sum_{i=1}^{n}(s_i\Delta t_i) = \frac{2.3}{4\pi T_o}\sum_{i=1}^{n}\left(Q_i\Delta t_i\log\frac{2.25T_o t_i}{r_c^2 S}\right)$ (4)

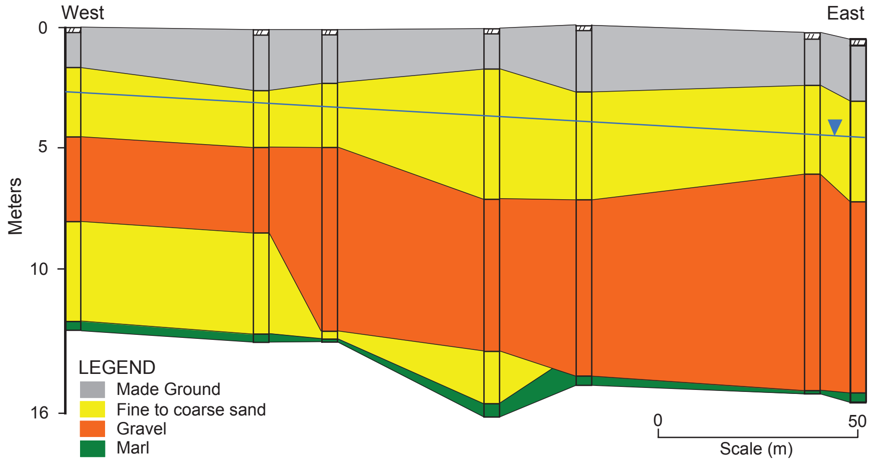


Figure 3. West to East schematic cross section of the local upper strata.

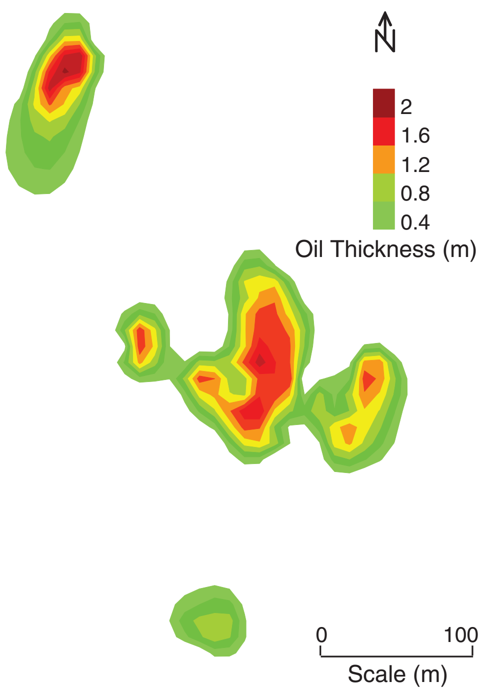


Figure 4. Distribution and thickness of the oil in meters using kriging interpolation at t_0.

From ground surface to the Tertiary marl, this upper strata is vertically and horizontally heterogeneous due to a large grain-size distribution variation from fine sand to gravel. In addition, thin silty lenses are randomly encountered across the site. Groundwater beneath this site is unconfined with a seasonal fluctuation between −2 and −3.5 m below ground surface. The groundwater conductivity has been estimated from aquifer pumping tests at four different locations across the site. The values are in close agreement, ranging between 2.6 and 3×10^{-4} m/s. The hydraulic gradient is 0.0025 from south-west to north-east.

The soil and groundwater baseline study highlighted four main areas where oil was encountered; the total extent is over approximately 15,000 m^2. The oil thicknesses measured in 120 wells ranged from a few centimeters to 2.5 m (Figure 4). Due to the long history of the site, and complexity of the industrial processes, the nature and the released volume of oil are unknown. The oil properties classify it as mostly lubricant oil. With the use of a number of oil products over the years, oil mixing in the soil, precipitation and different degradation stages, there is some spatial variability of the oil physical properties (Table 2). The oil viscosity and relative density have been measured on 25 oil samples, and the interfacial tension on four samples.

Table 2
Main Physical Properties of the Oil

Product relative density (15 °C)	0.85 to 0.88
Viscosity (15 °C)	90 to 115 cP
Oil/water interfacial tension	16 to 18 dynes/cm
Oil/air interfacial tension	29 to 31 dynes/cm

Long-term groundwater monitoring including analysis for total petroleum hydrocarbon (C6-C40 fraction) showed that the oil solubility is limited and the oil has not created a dissolved hydrocarbon plume down gradient.

After controlling the active sources that contributed oil to the soil, remediation was started in 2011. Based on pilot test results, enhanced dual phase extraction (removing oil and water) was implemented in three areas. One of these areas contains chlorinated solvents mixed with the oil and is equipped with static oil skimmers and not dual phase extraction, to avoid chlorinated solvent migration deeper in the aquifer. The recovery system consists of 120 extraction wells connected to a collection system and central remediation unit with 40 m^3 oil storage capacity. Ten other wells are distributed across the oil collection areas for monitoring purposes. After 18 months of extraction, 90 m^3 of oil were recovered.

Based on previous conclusions showing that performing a bail-down test in a well with less than 30 cm of oil is not appropriate (Kolhatkar et al. 1999), testing was performed only for wells exhibiting more than this minimum oil thickness. Information on oil mobility was collected during the environmental site assessment, before the start of remediation (t_0). At t_0, 101 wells exhibited more than 30 cm of oil and were tested. At t_1 (6 months after start of remediation) and t_2 (18 months after start of remediation), respectively, 99 and 89 wells exhibited more than 30 cm of oil and were again tested. The entire oil extraction system was stopped 72 h before bail-down tests were performed to allow the fluids to equilibrate in the wells. To make the oil thickness and the oil transmissivity estimates comparable, the field tests were performed at periods of the year when the groundwater levels were similar, that is, within 5%.

All bail-down tests were performed, following the standard field method as described in ASTM Standard E2856-13. The main steps of the test were:

- Measurement of the oil/air and oil/water interface levels at equilibrium (pretest) conditions using an interface probe (Model SOLINST SI30).
- Removal of the entire oil thickness from the well, as quickly as possible. This oil extraction was performed using a peristaltic pump to remove only the oil phase. The flow rate of the pump was set at 1.5 m^3/h.
- Monitoring the oil/air and oil/water interface levels during the time the oil thickness in a well recovered to (or nearly to) pretest levels. This monitoring was performed with a manual interface probe (Model SOLINST SI30). The standard approach was to measure the interface levels every minute during the first 5 min of the test, then measurements were performed at 10 min, 15 min, 30 min, 1 h, 4 h, 9 h, 12 h, 16 h, 20 h, 24 h, 48 h and 72 h after the test commenced. After 3 days, the oil thickness in a well recovered to (or nearly to) pretest levels.

All data sets were interpreted using the following methods:

- Modified Cooper solution (Beckett and Lyverse 2002): resulting transmissivity is noted as T-Cooper.
- Modified Bouwer and Rice (Kirkman 2013): resulting transmissivity is noted as T-B&R.
- Modified Jacob and Lohman (Huntley 2000): resulting transmissivity is noted as T-Jacob.

For practical reasons, the interpretation of the bail-down tests for the three selected methods was performed using a specifically developed software interface (programmed in Python). The interface allows a user to overlay and visualize the oil/water interface, the oil/air interface, the potentiometric surface evolution during the time of the test and the data plot for all three analysis methods.

From the data plot, the transmissivity values were automatically calculated using the Kirkman solution (Equation 5). With respect to the Cooper approach, the curves H/H_0 and the equation solution were manually fitted using T_o and S as variable parameters (Equation 3). Last, for the modified Jacob and Lohman solution the two sides of Equation 4 are plotted and the sum of the squared residuals is automatically calculated over time. Values of T and r^2S are iteratively adjusted by the user to minimize the sum of squared residuals. For both the modified Cooper, and Jacob and Lohman solutions, the starting S values were estimated at 0.15 to represent a reasonable porosity value for the site (mixed fine to coarse sand).

Results

The review of the results focused on three main topics:

1. Description of the quality of the data sets, the nature of recharge to the wells and the quantity of data suitable for analysis with the Bouwer and Rice approach.
2. Review of the oil transmissivity values and review of consistency of results between the three analytical approaches.
3. Assessment of the changes in oil thickness and oil transmissivity during remediation.

Description of the Collected Data

The first evaluation step was to plot the J-ratio for all data sets in order to determine whether data can be interpreted using the modified Bouwer and Rice solution, and to understand the nature of the recharge to the wells. The J-ratio, which is the relation between the drawdown and the oil recharge to the well, was calculated using the Kirkman (2013) approach. Results are shown in Table 3.

Data were grouped based on the quality of the relation in J-ratio graphs. Three groups were defined based on the squared coefficient value positing that $R^2>0.8$ represents a "linear relation" (Type 1), $0.8>R^2>0.5$ represents a "good correlation" (Type 2), and finally $R^2<0.5$ represents a "limited relation" (Type 3).

The second part of Table 3 describes the nature of the recharge of the well, based on the values of the J-ratio. If the

Table 3

Synoptic View of the Collected Data

Summary of Comparisons Between Drawdown and Oil Recharge to a Well (J-Ratio)								
Linear Relation (Type 1) ($R^2_{\text{J-ratio}}>0.8$)			Good Correlation (Type 2) ($0.8>R^2_{\text{J-ratio}}>0.5$)			Limited Relation (Type 3) ($R^2_{\text{J-ratio}}<0.5$)		
144 of 289 tests (49.8%)			53 of 289 tests (18.4%)			92 of 289 tests (31.8%)		
Distribution of J-ratio types								
$J=-(1-\rho_o)$ (Type 1 a)	$J\approx-(1-\rho_o)$ (Type 1 b)	$J=-1$ (Type 1 c)	$J=-(1-\rho_o)$ (Type 2 a)	$J\approx-(1-\rho_o)$ (Type 2 b)	Other (Type 2 c)	$J=-(1-\rho_o)$ (Type 3 a)	$J\approx-(1-\rho_o)$ (Type 3 b)	$J=-1$ (Type 3 c)
80	58	6	11	41	1	6	82	4

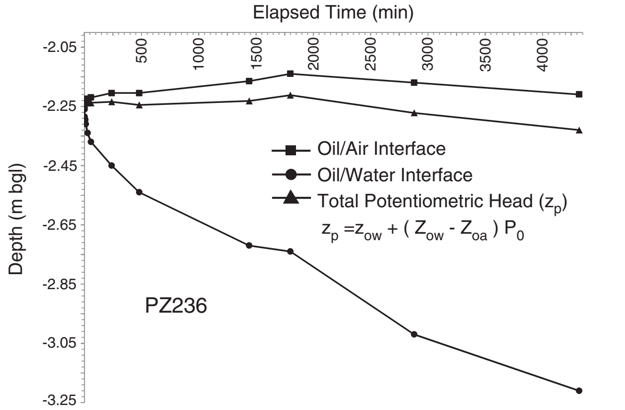


Figure 5. An example of oil/air and oil/water interface levels during the test (PZ 236).

J-ratio is equal to $-(1-\rho_o)$, the total potentiometric surface remains constant during the test, which means that water rapidly recharges the well before oil comes back (Type a). Type b groups all the other data sets for which the J-ratio is not strictly equal to $-(1-\rho_o)$ but the total potentiometric variation during the test is less than 5% of the original value (Figure 5). Finally, Type c represents data sets for which the J-ratio is equal to -1, meaning that depth to the water is constant during the test and no water enters the well after the oil is bailed.

The analysis of the J-ratios shows that a linear relation between the oil drawdown and the oil recharge into the well exists for 50% of the bail-down tests (Type 1). For 18% of the wells (Type 2) the linear relation exists with more spread among the data points, while for 32% (Type 3) the relation is negligible. Therefore, within the data set we can consider that 68% (Types 1 and 2) are suitable for using the Bouwer and Rice solution (Kirkman 2013).

As there is a discussion about the validity of the assumption of a constant potentiometric head (Batu 2012; Charbeneau et al. 2013), this hypothesis was tested on our data set. It appears that, for the bail-down data set, 96% (Types a and b) verifies the assumption of a constant head with error of 5% or less. Among our data set, it appears that only 4% of the tests follow Lundy and Zimmerman's assumption of a constant oil/water level (Type c).

The consequence of the previous observation is that, for most of the studied examples, the J-ratio is close to $-(1-\rho_o)$. However, the coefficient of correlation on the J-ratio curves was quite poor for 32% of the samples (Type 3). A detailed analysis of these plots showed that the poor correlations encountered in the J-ratio curves are mostly due to field measurement errors.

A simple method was developed to allow the use of these data sets. The classical approach for the raw data analysis consists of plotting the oil/air interface drawdown $s_{1(t)}$ versus elapsed time after the oil is bailed from a well. To allow the use of the modified Bouwer and Rice or the modified Cooper et al. approaches, after the filter pack recharge period, the oil/air interface drawdown should show a linear decrease with time (shown in section A in Figure 6). Among the total of 289 bail-down tests, 85 bail-down tests (29.4%) meet this condition.

The relatively small ratio of data that can be interpreted by the modified Bouwer and Rice or the modified Cooper approaches can be explained by the difficulty of measuring the interface levels as emulsions or bacteria are often present in the wells, and the measurement error introduced by the use of an interface probe. Moreover, it is quite common that the oil/air interface moves only over a short distance during the test, which induces relatively large measurement error and leads to a data set that cannot be interpreted. Figure 6 shows an example with data from PZ 222 at t_0 where the measurement error induced at first a small decrease in and then a constant level of the oil/air interface at the beginning of the test.

In order to increase the number of data sets which can be interpreted and to minimize the measurement error as described above, a slight modification in the interpretation of the drawdown is proposed. In Equation 5 which presents the Bouwer and Rice-modified solution (Kirkman 2013), the drawdown considered ($s_{1(t)}$) is the oil/air interface drawdown.

Using the symbols from Figure 2, if $L_{o(t)}$ represents the oil thickness at time t, or $L_{o(t)} = b_{1(t)} + b_{2(t)}$, and $s'_{(t)} = s_{1(t)} + s_{2(t)}$, then,

$$\frac{\partial L_{o(t)}}{\partial \mathrm{t}} = -\frac{\partial s'_{(t)}}{\partial \mathrm{t}} \tag{7}$$

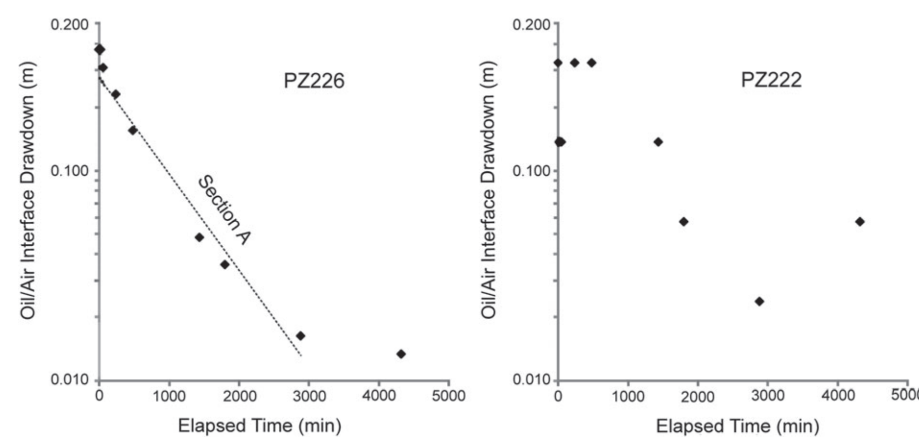


Figure 6. Bail-down test data sets for piezometers PZ 222 and 226 at t_0.

Based on the nature of the recharge of the wells described above, we can assume that the water level remains approximately constant during the test for all the wells, which gives:

$$s_{1(t)} = s'_{(t)}(1-\rho_o) \text{ and, } ds_{1(t)} = ds'_{(t)}(1-\rho_o)$$

Therefore Equation 5 becomes,

$$T_o = \frac{r_c^2 \ln\left(R_e/r_w\right)}{-2J}\frac{1}{t}\ln\left(\frac{s'_{(t0)}}{s'_{(t)}}\right) \quad (8)$$

The input data are then the oil thickness instead of the oil/air interface level. Using this modified approach, which considers the total drawdown ($s'_{(t)}$) of both oil and water, the quantity of data sets suitable for analysis increases to 202 (69.9%). Table 4 shows the ratio of data which can be interpreted using s_1 or s' drawdown, based on the J-ratio correlation and on the nature of recharge to the wells.

Table 4 should be read as follows: 67% of the 80 bail-down tests (Type 1a) for which (1) the J-ratio presents a good correlation ($R^2 > 0.8$) and (2) the total potentiometric surface remains constant during the test ($J = -(1-\rho_o)$), can be interpreted using $s_{1(t)}$. The percentage of bail-down tests which can be interpreted using $s'(t)$ for the same bail-down type (Type 1a) reaches 100%.

It is clear from this analysis that the closer the J-ratio R^2 is to 1 and the closer the J-ratio value is to $-(1-\rho_o)$, more data sets could thus be interpreted using either the modified Bouwer and Rice or Cooper et al. approach.

Oil Transmissivity Values

For the whole measurement series, the oil transmissivity (T_o) values ranges from:

- 5.4×10^{-4} to 1.7×10^{-6} m²/min with modified Bouwer and Rice method.
- 9.7×10^{-4} to 1.2×10^{-6} m²/min with the modified Jacob and Lohman method.
- 5.7×10^{-4} to 1.0×10^{-6} m²/min with the modified Cooper method.

The median values of oil transmissivity calculated using the three methods are very close (T-B&R = 3.8×10^{-5} m²/min, T-Cooper = 3.0×10^{-5} m²/min and T-Jacob = 3.9×10^{-5} m²/min). For both Cooper and Jacob methods, the final S values minimizing the sum of squared residuals are fairly consistent with an unconfined aquifer as they range from 0.04 to 0.45.

Figure 7 shows that T-B&R and T-Cooper are well correlated. The gray symbols ("all data"—Type 3) indicate a limited correlation of the J-ratio. These data sets (Type 3) show an increased scatter of data in the plotted results suggesting a decrease in the observed correlation between the oil transmissivity obtained with the modified Bouwer and Rice, and Cooper et al. approaches.

Figure 8 also shows a good correlation between the oil transmissivity values obtained using the modified Jacob and Lohman method and the modified Bouwer and Rice. This plot of data only considers the "selected values" of the analysis presented above (Figure 7).

This analysis gives a reasonable indication that the oil transmissivity values obtained with one of these approaches (T-B&R, T-Cooper, and T-Jacob) are good estimated values.

Oil Thickness and Oil Transmissivity Development

Another objective of the study was to assess the impact of remediation on the oil mobility.

Comparison of the oil transmissivity values calculated with the same method (modified Bouwer and Rice approach) shows an observed decrease of oil transmissivity (T_o) over time (Figure 9).

Eighteen months after oil extraction started, the average oil transmissivity value decreased by 52%. T_o increased slightly during the six first months of extraction (13%), then dropped significantly (−45%).

As shown in Figure 10, this trend was also observed in the average measured oil thickness in the wells (slight initial increase during the first months of extraction followed by a significant drop of 23% over the period). However, oil transmissivity and oil thicknesses measured in the wells are not clearly correlated.

The trends shown in Figures 9 and 10 highlight the complex relationship between oil thickness observed in a well and oil transmissivity which is unique for each well, as local soil heterogeneity is always encountered.

The absence of a relationship between the oil thickness measured in the wells and the T_o values is clearly shown by Figure 11 which superimposes the oil thickness distribution and the calculated oil transmissivity values (T-B&R) at t_0. and t_2.

Table 4
Proportion of Interpretable Data Using s_1 and s'

	Percentage of the Data Sets Suitable for Analytical Interpretation Using s_1 or s'								
	$R^2_{\text{J-Ratio}} > 0.8$			$0.8 > R^2_{\text{J-Ratio}} > 0.5$			$R^2_{\text{J-Ratio}} < 0.5$		
	$J = -(1-\rho_o)$ (Type 1 a)	$J = -(1-\rho_o)$ (Type 1 b)	J = −1 (Type 1 c)	$J = -(1-\rho_o)$ (Type 2 a)	$J = -(1-\rho_o)$ (Type 2 b)	J = −1 (Type 2 c)	$J = -(1-\rho_o)$ (Type 3 a)	$J = -(1-\rho_o)$ (Type 3 b)	J = −1 (Type 3 c)
Number of tests	80	58	6	11	41	1	6	82	4
Interpretable using s_1 (%)	67	34	0	9	19	0	0	2	0
Interpretable using s' (%)	100	81	17	91	66	0	33	40	50

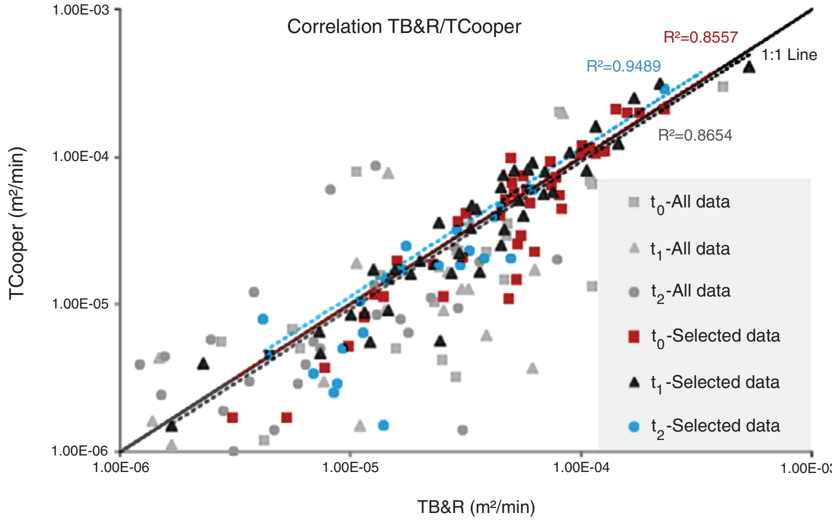


Figure 7. Correlation between the oil transmissivity values estimated by the modified Bouwer and Rice approach and by the modified Cooper et al. approach.

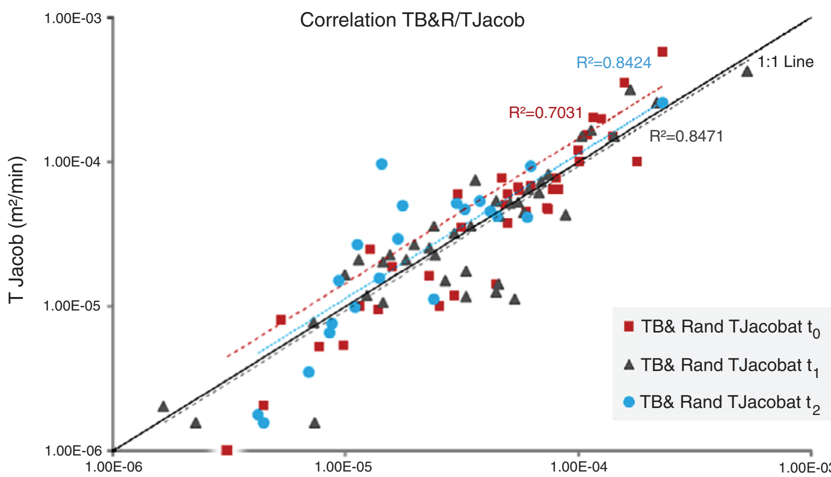
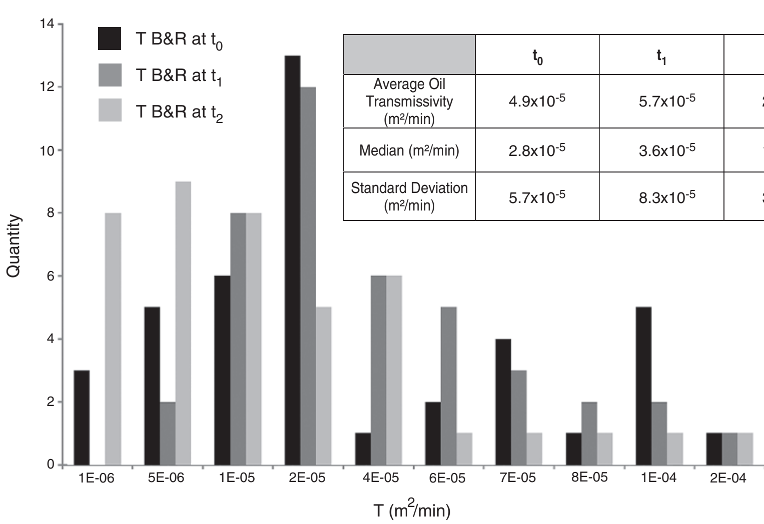
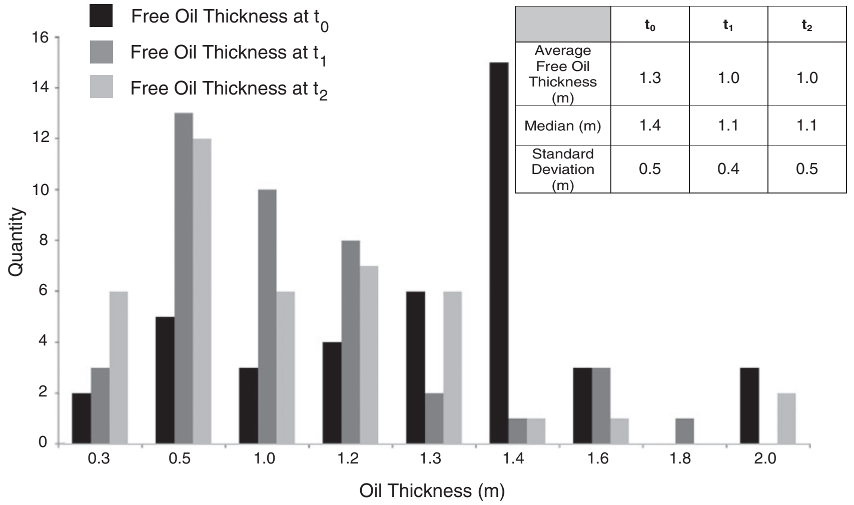


Figure 8. Correlation between the oil transmissivity values estimated by the modified Bouwer and Rice approach and by the modified Jacob and Lohman approach.



	t_0	t_1	t_2
Average Oil Transmissivity (m²/min)	4.9×10^{-5}	5.7×10^{-5}	2.6×10^{-5}
Median (m²/min)	2.8×10^{-5}	3.6×10^{-5}	1.2×10^{-5}
Standard Deviation (m²/min)	5.7×10^{-5}	8.3×10^{-5}	3.4×10^{-5}

Figure 9. Oil transmissivity values and main statistics before, 6 months after, and 18 months after start of remediation.



	t_0	t_1	t_2
Average Free Oil Thickness (m)	1.3	1.0	1.0
Median (m)	1.4	1.1	1.1
Standard Deviation (m)	0.5	0.4	0.5

Figure 10. Oil thickness in the wells before, 6 months after, and 18 months after start of remediation.

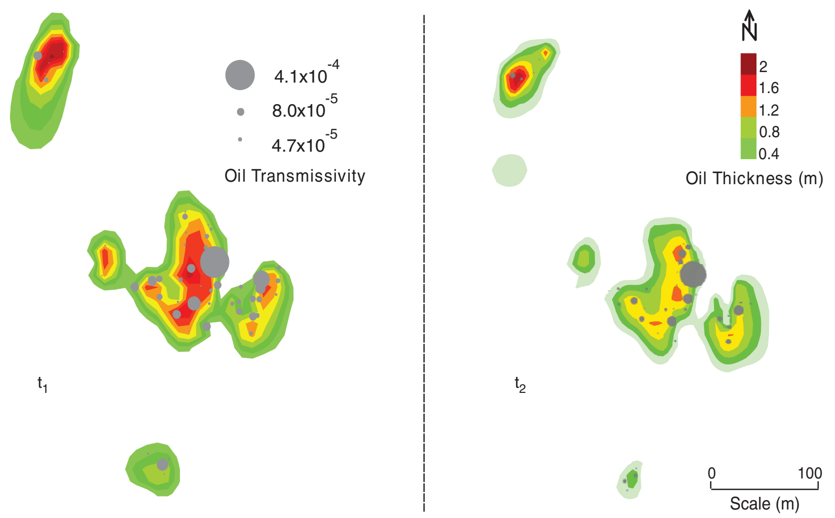


Figure 11. Oil thickness in wells (at t_0 and t_2) and T_o values distribution (at t_0 and t_2).

Summary and Discussion

To our knowledge this is the first study in which hundreds of bail-down tests completed at one test site were compared including spatial and temporal distributions. Although the results have some generality they are applicable mainly to data collected from wells placed in soils of similar grain size, that is, sand and coarse sands with some interbedded silt layers that are contaminated by degraded, viscous lubricating oil.

The relatively slow recharge to a well observed with viscous straight oil (80 to 120 cP) suggests that during the bail-down test, the interface depth measurements can be taken manually using an interface probe. However, this study shows the difficulty of interpreting bail down tests with field measurements made with a manual interface probe. It may be explained by the site-specific conditions observed such as bacteria development within the wells, and the presence of an oil/water emulsion between the oil phase and the groundwater which lead to measurement uncertainties. Therefore, it is suggested that the interface depths be automatically measured using an acoustic range finder and a transducer as suggested by Hampton (2003). In cases where a nearly stable potentiometric level is encountered and the values were obtained manually, we suggest a solution of using s' that has allowed the interpretation of more data points. We note that while this approach allowed interpreting more data sets, the overall quality of the correlation decreased. Therefore, this method is somewhat helpful in such conditions but it remains preferable to use automated data acquisition.

The oil transmissivity values obtained from the three bail-down test interpretation methods (modified Bouwer and Rice, modified Cooper et al., and modified Jacob and Lohman) were compared and these results show good correlation across the project site. This correlation is based on a large number of values (289) and gives confidence in these transmissivity estimates. A direct measurement of correct oil transmissivity depends on obtaining an undisturbed core sample and completing a complex, physical analysis. The collection and handling of numerous core samples for these complex measurements are not feasible across a large project site. The authors therefore conclude that representative values for oil transmissivity can be estimated using these methods and is the most relevant approach for a large-scale project. Data not within the theoretically defined range of conditions listed in Section *Oil Bail-down Test Theory* (drawdown assumption, pseudo steady-state) does not appear to be a basis for restricting the use of these analytical solutions as suggested by Batu (Charbeneau et al. 2013). The poor sensitivity to these assumptions may be explained by the viscosity difference between the oil and the water (oil viscosity being much greater than water viscosity for this study case). Under this condition, removing oil from the wells slightly affects only the oil level in the formation, therefore: (1) the true drawdown in the formation can be considered as negligible without regard to the drawdown in the well and (2) oil movement in the formation can be assumed to be pseudo steady state.

Secondly, this study shows that the simplifying assumption made by Huntley (Huntley 2000) to allow the drawdown calculation for the modified Bouwer and Rice approach is consistently met. However, the J-ratio introduced by Kirkman (2013) allows applying the Bouwer and Rice solution regardless of the nature of recharge of the well. Therefore, a detailed analysis of the nature of recharge of the well is valuable to understand the oil behavior at the site, but not critical to apply Bouwer and Rice. The encountered stability of the total potentiometric level is likely linked to the site-specific conditions: an unconfined water table beneath most of the site and a mostly coarse-grained lithology. However some of the wells were located at places where silts are more predominant and we did not see different behaviors in these wells. Again, the oil viscosity may explain the stable potentiometric level, as the oil tends to move slowly while the water will almost instantaneously compensate the head difference. Therefore, the above assumptions and analyses will apply best to similar sites with viscous lubricating oil. Wells with less dense and less viscous products like fuels will respond and equilibrate faster; and will impact which underlying assumptions and methods work best for analyzing the bail-down tests on those sites.

Finally, in our analysis we noted a decrease in both oil thickness and oil transmissivity during the 18 months of remediation. One can note here that the trend in oil thickness measured in the wells should be interpreted taking into consideration the variation of the total potentiometric level between the different periods of analysis. As described by several authors (e.g., Marinelli and Durnford 1996) when water level rises in a well, the oil thickness tends to decrease and vice versa. In our study, the total potentiometric surface is approximately at the same level at t_0 and t_2, while it is 5% lower at t_1. Therefore, one can conclude that the oil collection project is efficiently reducing the oil saturation in the porous medium as suggested by the decrease of the oil thickness and oil transmissivity for an equivalent total potentiometric surface.

In typical areas with various grain sizes, no correlation between oil thickness and oil transmissivity exists at the study site. Only in a homogeneous system would one expect to see a correlation. In a heterogeneous system, oil transmissivity is more related to the texture of the sediment than the oil thickness. This dependency on soil texture is even greater in a water-saturated system, as coarser soils have largely higher oil saturations, leading to orders of magnitude higher conductivity than finer soils for the same thickness. Consequently, thin coarse soils may have oil transmissivities that are orders of magnitude higher than thick finer soils layers (Huntley et al. 1994). The measured decrease in both oil transmissivity and thickness is also not correlated over time, although both decreased over time.

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Notations

ρ_o oil relative density
b aquifer thickness (m)
J Kirkman J-ratio
L length of well screen immersed in water (m)
Q water discharge (m^3/s)
Q_i oil discharge at t_i (m^3/min)
R_e effective radius of the well (m)
r_c well casing radius (m)
r_w borehole radius (m)
S storage coefficient
s_0 water drawdown at t_0 after bailing (m)
s_i oil drawdown at t_i (m)
s_t water drawdown at t after bailing (m)
$s_{1(0)}$ oil drawdown at t_0 (m)
$s_{1(t)}$ oil drawdown at t (m)
$s'(t)$ total drawdown including oil drawdown and water drawdown (m)
T water transmissivity (m^2/s)
T_o oil transmissivity (m^2/min)
t elapsed time (sec for water equations and min for oil/water equations).
(u) Bessel function
$z_{ao(0)}$ oil/air interface level at t_0 (m)
$z_{ao(t)}$ oil/air interface level at t (m)
$z_{aw(0)}$ air/water interface level at t_0 (m)
$z_{aw(t)}$ air/water interface level at t (m)

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