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Mobilité de l'huile dans le sol et optimisation de son extraction

Cédric Palmier

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THÈSE DE DOCTORAT DE L'UNIVERSITÉ MICHEL DE MONTAIGNE - BORDEAUX 3

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présentée par

Cédric PALMIER

pour obtenir le grade de:

Docteur de l'Université Michel de Montaigne

Oil Mobility Estimation and Recovery Optimization

Directeur de thèse: M. Olivier ATTEIA

Soutenue le 9 Novembre 2016 devant le jury composé de:

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Chapter 1

Introduction

Chemical products have largely been used since the last century in a wide range of industries. Accidental releases of these products from underground storage tanks or during manufacturing operations cause subsurface contamination. In Europe, soil contamination is a widespread problem of varying intensity and significance. Most of the contaminated sites are concentrated in former mining areas and highly urbanised or industrial zones. The European Environment Agency (EEA) collects data on soil contamination and cleanup. Based on the current reporting comprising 27 countries, about 1 170 000 potentially contaminated sites have been identified (Van Liedekerke *et al.*, 2014). Caution should be taken when considering the total number of potentially contaminated sites as there are substantial differences in the underlying site definitions and interpretations that are used in different countries across Europe. In some countries, "potentially contaminated sites" is understood to be those sites identified by mapping potential pollution activities (e.g.: Belgium, Netherlands, France), but in other countries more direct evidence, such as analytical data, are needed to qualify a site as being potentially contaminated (e.g.: Austria, Hungary, Norway). Although the distribution of soil pollution sources across economic sectors differs from country to country, industrial activities are responsible for over 60% of Europe's soil pollution (the oil sector accounts for 14% of this total). As reported in 2011 to the European Environment Agency, the relative importance of the different contaminants is stable over the last decade, except for a decrease in the share of sites associated with chlorinated hydrocarbons in groundwater. The distribution of contaminant is similar for both liquid and soil matrices. The most frequent contaminants are mineral oils and heavy metals (Figure 1.1).

Since 1990, contaminated sites in France are registered in two data bases. "Basias" database groups the old industrial sites and other service activities which potentially created a soil and groundwater contamination. Currently 300 000 to 400 000 sites are listed covering approximately 10 000 hectares. "Basol" database groups the sites for which a remediation plan is in place to mitigate the risk for human health and for the environment. In 2014, 4250 sites were listed (Antoni *et al.*, 2013). As for Europe, industrial activities are responsible for over 60% of France's soil pollution. The contaminated sites are mainly encountered in

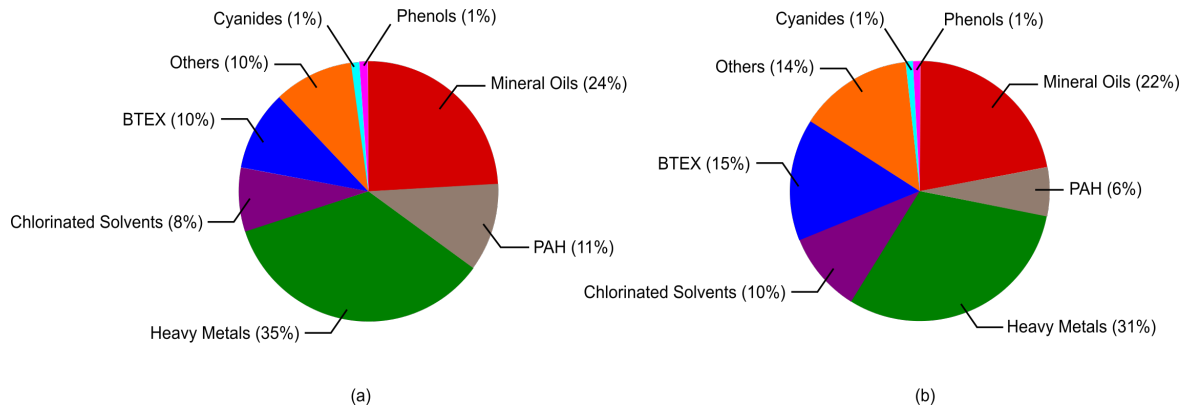


Figure 1.1: Contaminant ratio in (a) contaminated soil, and (b) groundwater in Europe, 2011 (following Van Liedekerke *et al.* (2014))

the regions where historically the mining and industrial activities were the most developed: Île-de-France, Lorraine, Nord and Rhône-Alpes.

Despite slight differences in the distribution of the contaminants as compared with the European level, the most frequent contaminants present in the soil and groundwater across France are the mineral oils and the heavy metals (Figure 1.2).

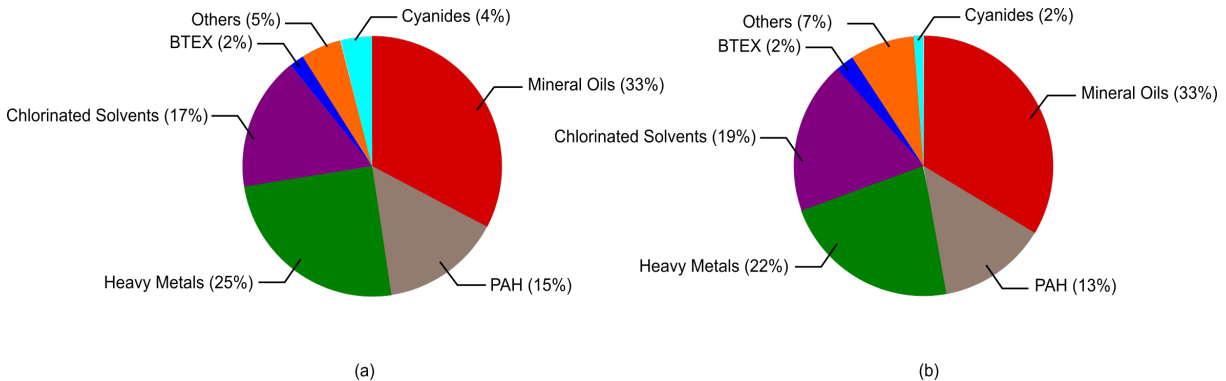


Figure 1.2: Contaminant ratio in (a) contaminated soil, and (b) groundwater in France, 2012 (following Antoni *et al.* (2013))

Due to its large-scale use in various applications, from a quantitative perspective, mineral oil appears to be one of the largest contaminants in the subsurface. Its ratio is similar in soil and in groundwater. In France, mineral oil is the pollutant for a third of the contaminated sites, whereas mineral oil concerns a quarter of the contaminated sites in Europe.

The overall targets and obligations for site investigation and remediation are very close in France and in the rest of Europe. The overarching policy objective is to achieve a level of quality of the environment where manmade contaminants on sites do not give rise to significant impacts on or risks to human health and ecosystems.

In Europe, legal requirements for the general protection of soil have not been agreed and only exist in some Member States. However, the Integrated Pollution and Prevention Control Directive (IPPC 2008/1/EC) requires that operations falling under its scope do not create new soil contamination, and legislation not aimed directly at soil protection (e.g.: the Water Framework Directive, the Waste Framework Directive and Landfill Directive) provides indirect controls on soil contamination and requirements for its management where applicable. Furthermore, the Directive on Industrial Emissions (IED 2010/75/EU) provides a regulatory framework to prevent emissions to soil from large industrial plants; it has repealed the IPPC Directive with effect from January 7, 2014. Notwithstanding these and similar controls in non EU Members States, significant new site contamination still occurs as a result of accidents and unlawful activities. One can recognize that the legal approach in Europe is focused on the prevention, without strong requirements regarding the remediation obligation of the State Members. In some fashion, the obligation for remediating is only driven by environmental quality objectives, imposed by the Member States.

At the national level, in France, prevention against soil and groundwater contamination is mainly driven by the legislation which manages the classified installations ("Installations Classeées pour la Protection de l'Environnement" - ICPE). Besides the prevention itself, the remediation strategy is based on the legal texts from February 2007. The overall approach is risk driven, with a general objective to minimize the risk to an acceptable value for the use of the site. The concept to make the site "suitable for its current or known future use" is a common approach in the European Member States which have a robust legal structure to manage the contaminated sites (e.g.: France, Germany, United Kingdom, Netherlands). The obligation in France, from the legal texts of February 2007, goes a bit further requiring a site to be remediated as long as i) the asymptote of concentration following treatment is not reached with the current technique, and ii) an alternative cost-effective technique exists to optimize the site cleanup. However, this obligation may be negotiated case by case and varies across the regions. Therefore, in France the requirement is to remove any liquid phase as long as a cost-effective technique exists. In other countries, like in United Kingdom, the risk driven approach is stronger, and in many cases, free oil in the subsurface may not lead to an Agency obligation for cleanup actions.

Generally, the priority for pollutant containment or cleanup actions is based on its toxicity, environmental persistence, mobility and bio-accumulation. Based on this approach, remediation projects usually target heavy metals, polycyclic aromatic hydrocarbons, and solvent contaminated land. The oil usually presents a low mobility and the risk to the human health and to the environment is low when compared to other pollutants. However, oils may present two main risks depending on their nature and on the ground conditions. First, dissolved phase may contain toxic compounds as polycyclic aromatic hydrocarbons which could migrate downgradient of the liquid phase, as dissolved component of the groundwater. Secondly, if certain soil and groundwater conditions are satisfied, the oil may be degraded through a long-term process, involving the methanogenesis and other degradation processes. This degradation process occurs under anaerobic conditions. The breakdown products are methane and dihydrogen sulfide. Furthermore, the fact that humans can tolerate exposure to mineral oil without health concerns has not been proven convincingly. Therefore, considering that oil is one of the common contaminants in soil and groundwater across European

countries, and its potential risk for the human health and the environment, it is a key interest to understand its mobility and behavior in subsurface to improve site assessment and cleanup actions.

As the mineral oils present densities lower than water, they are generally referred to as Light Non-Aqueous Phase Liquids (LNAPL). The United States Environmental Protection Agency defines LNAPL as: one of a group of organic substances that are relatively insoluble in water and are less dense than water. LNAPLs, such as mineral oil, tend to spread across the surface of the water table and form a layer on the top of the water table. Gasoline, diesel, crude oil, lubricants and heating oils are common examples of LNAPL. In this manuscript, the term "oil" is used when referring to a LNAPL. If only water is present in the formation, this situation is called "single-phase system" in this manuscript. If oil and water are present in the formation, this situation is called "two-phase system" in this manuscript.

When released in the subsurface, the general oil migration is governed by gravity, viscous forces, and capillary forces. Its migration and distribution in the subsurface is affected by soil heterogeneities. In the unsaturated zone, low-permeable layers act as a barrier and inhibit the vertical migration and force the oil to move laterally. In a high permeable layer the oil migration is fast and often takes place as finger flow as shown in Figure 1.3.

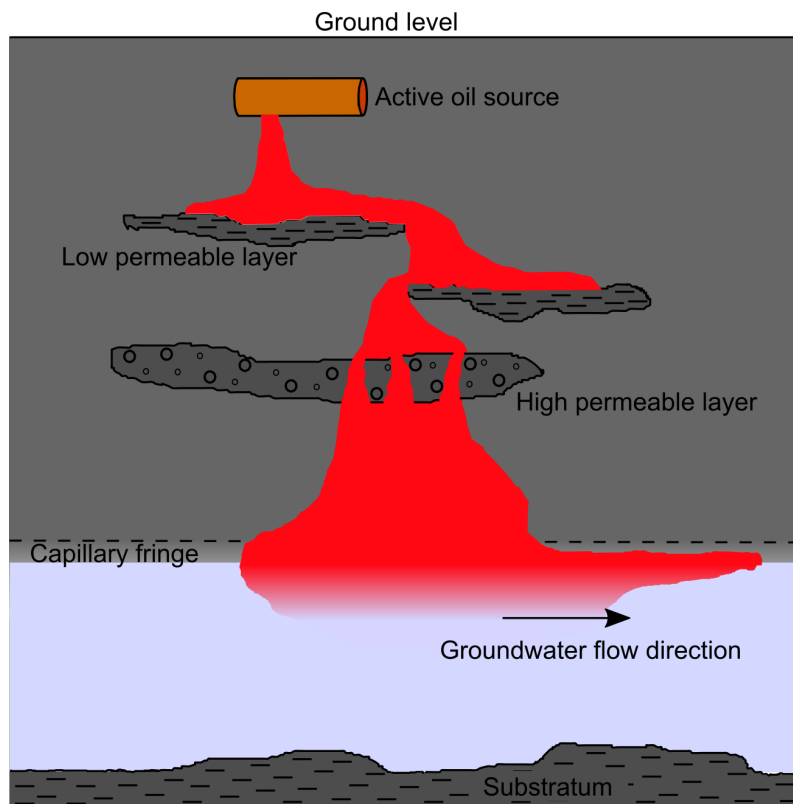


Figure 1.3: Schematic view of oil migration in the subsurface from an active source (after Mayer and Hassanizadeh (2005))

The early oil migration and distribution conceptual model developed in the 1980's was based on a "pancake" conceptualization (Ballesterro *et al.*, 1994). In this conceptualization, it was assumed that the oil in the unsaturated zone migrates vertically under gravitational forces until the water table is reached, at which time the oil spreads horizontally as a continuous single-phase fluid. The oil is assumed to "float" on the groundwater as a distinct layer. In this model, the oil fills the entire pore spaces over a thickness of soil equal to the oil thickness observed in the adjacent well. This conceptualized model is inaccurate as it ignored the critical influence of the capillary forces, and usually it over-estimates the oil volume and recoverability. Later, based on the work by Dullien (1979), Lenhard and Parker (1990) and Farr *et al.* (1990) a more accurate oil migration and distribution conceptual model has been proposed. In these "multi-phase" models the oil does not continue to migrate vertically as a separate layer (pancake) but, instead, exhibits behavior similar to an iceberg at sea, largely submerged and, in some cases, at significant depth below the water table (Charbeneau, 2003). In these multiphase conceptualizations, oil, water and air coexist in the porous media where oil is present, and the oil migration and distribution under vertical equilibrium results i) from the fluids properties (oil, air and water), ii) from the porous media characteristics and, iii) from complex interactions of forces which act on the system fluid/solid.

Based on these legal obligations, but also on corporate good practices, the site owners are more and more involved in oil remediation projects. Most of the time, the approach consists of removing the oil phase from extraction wells. It may involve two different approaches, i) the static extraction without water removal (e.g.: floating skimmer, oleophilic belt), or ii) the dynamic extraction which combines oil skimming and water extraction at the same location (e.g.: dual-phase extraction). The dynamic approach usually enhances the oil recovery as it creates a greater gradient in the oil phase that increases the oil flow to the recovery well, but may involve water treatment.

For a remediation project manager, the main objective is to anticipate the timing, the cost and the performance of the remediation approaches, in order to implement the cost-effective solutions that would allow his or her company or organisation to reach a reasonable end-point. In Europe, companies that are due to remediate contaminated sites, usually base the design on oil thicknesses measured in the monitoring wells densifying the number of extraction wells in the areas where the oil thicknesses in the monitoring wells are the most significant. This simplified approach ignores the theory from the "multi-phase" model and may lead to recovery well networks that are not optimal. Indeed, due to capillary forces a recovery well located in very fine sand that exhibits 1 m of oil will be much less productive than a recovery well located in gravels with the same oil thickness or even less. The oil volume and mobility in the gravels will be significantly higher than in the fine materials. In addition, this approach which does not consider the oil mobility does not allow to estimate the timing of the recovery project. In the United States of America, the situation is slightly different. In 2009, an ASTM (American Society for Testing Materials) committee including three members from universities (R.Charbeneau, D.Huntley, and D.Hampton), three members from state regulatory agencies, twelve members from oil companies (including A.Kirkman, D.Lundy) and consulting firms was created. This committee was tasked with revising an earlier standard for remediating sites with significant free product accumulations.

The goal of this industry-dominated group was to come up with recommendations for oil mobility evaluation as an alternative to determining oil recoverability using oil thickness measurements from wells. By 2011 the group delivered those recommendations, ultimately leading to ASTM E2856-13, Standard Guide for Estimation of LNAPL Transmissivity. Today, this standard is actively promoted by ITRC (Interstates Technology and Regulatory Council) in their webinars and face-to-face training.

Some of the reasons why the oil mobility is rarely used by the European remediation companies would be:

- The oil mobility is defined here by measuring the hydraulic oil conductivity or the oil transmissivity. At field scale, the oil transmissivity is estimated from field tests called bail-down tests that are performed in wells exhibiting free oil phase. Today the bail-down test is the predominant approach to estimate the oil transmissivity in the formation around the monitoring wells. However, and despite the fact that the oil transmissivity has become a recognized parameter used in various decision making processes across the U.S., the validity of the theory to interpret the bail-down tests is still being discussed (Hampton, 2003; Batu, 2013; Charbeneau *et al.*, 2013).
- An alternate to the field measurement of the oil mobility would be the laboratory measurement. However, this measure is tedious to perform (Sale and McWhorter, 2001) and there are difficulties for data acquisition. It is especially complex to collect samples that represent the true field conditions.
- Finally, there is probably a limited understanding on how oil mobility or thickness can be used.

Although it is difficult to predict the efficiency and duration of an oil recovery project, it is essential to make progress in this regard as it impacts a wide range of actors (i.e.: site owners, agencies). Therefore, the overall objective of this study is to improve the use of the investigation data to better anticipate the design efficiency and, to give a reasonable duration of an oil remediation project. In order to predict the long-term efficiency, the following questions have to be answered.

- To assess the oil mobility in order to assess the expected daily oil recovery. This requires the assessment of the validity of the bail-down test and to define which method of interpretation is the most relevant for a two-phase system.
- To determine the relationship between the bail-down test results and the nature of the adjacent formation. Which areas should be focused for recovery? Are the areas showing greater oil mobility randomly distributed?
- To define if a relationship between the oil mobility and the oil thickness in the monitoring wells exists. Should different recovery techniques be applied depending on the oil thickness?
- To estimate the duration of the oil recovery project. How to assess the validity of the oil mobility value? Over what time period should the oil mobility measurements be taken to allow a good estimate of the oil recovery project duration?

- To define when a recovery project can be stopped. What would be the most relevant criteria to make the decision? For example, when the oil mobility is below a certain value?

Oil mobility appears to be an important parameter to determine in order to answer some of the key questions presented above. But, the validity of the slug test, which is the unique simple approach to assess the oil mobility at field scale, is questionable. The uncertainties around the validity of the oil transmissivity value obtained, is essentially driven by the fact that the interpretation methods (modified Jacob and Lohman (Huntley, 2000), modified Bouwer and Rice (Lundy and Zimmerman, 1996; Huntley, 2000) and modified Cooper *et al.* (Beckett and Lyverse, 2002) methods) are all based on assumptions that are not consistently met during the test. The existing studies to confirm the bail-down test validity are limited (Huntley *et al.*, 1992; Krol, 1995; Kolhatkar *et al.*, 2000), and based on a very small number of tested wells (2 to 3). It is therefore necessary to make a robust validation of commonly used bail-down test interpretation methods, first at the laboratory scale with calibrated soil, and then in heterogeneous conditions, at field scale. Field validation would allow to confirm i) the outcome of the laboratory scale study for unknown and variable conditions (grain size heterogeneity), ii) if the oil mobility distribution is linked to the oil thickness distribution, and iii) to potentially determine some limitations of the approach and some potential improvements. Last, at field scale, authors (Kemblowski and Chiang, 1990; Marinelli and Durnford, 1996) have reported impacts of the groundwater table fluctuation on oil thickness in monitoring wells. For managing an oil recovery project, the follow-up of the temporal variations induced by the groundwater table fluctuation is thus a key subject. A clear description and understanding of this phenomenon may allow to better define site conditions, but also to assess its impact on the bail-down tests results.

The manuscript is structured as follows: Chapter 2 presents in the first part the theoretical background that explains the oil mobility in the soil, and in the second part the theory of the bail-down test interpretation for both single and two-phase systems. Chapter 3 presents the laboratory and field studies that have been conducted to assess the validity of the bail-down test methods of interpretation for a two-phase system. These studies further investigate i) the relationship between the bail-down test results and the nature of the adjacent formation, ii) how the oil thickness and the oil mobility are distributed across a widely studied site, and if a relationship exists between these two parameters, and finally how sensitive are the bail-down tests to the data collection process and other field conditions. Chapter 4 presents groundwater table fluctuation and its impact on the oil thickness in monitoring wells. The first part gives a detailed description of the observations for unconfined and confined oil layers. In the second part, a model is proposed to determine oil layer position in the formation and its hydraulic conductivity based on the oil thickness variations in the monitoring wells under groundwater table fluctuation conditions. This model has been tested on different cases from the field study. Finally, the last chapter proposes a discussion that enlarges the conclusions of Chapters 2 and Chapter 3 and provides a summary of the key outcomes of this work.

Chapter 2

Oil Mobility in Porous Media: A Theoretical Review

The first section of this chapter presents i) how the oil mobility is impacted by the soil and oil properties, and ii) how oil mobility can be measured at the core scale in single and two-phase systems. The second section presents the field measurement of the oil mobility.

2.1 Free Oil Behaviour in Porous Media and Oil Mobility Measurement at Laboratory Scale

The purpose of this part is to provide theoretical background to understand the oil behavior and mobility in the soil. The first part presents the fluid and soil properties involved in the oil distribution and mobility. The second part presents the parameters measured to describe the fluid distribution and mobility in the porous medium.

2.1.1 Fluids and Soil Properties

This part presents the main fluid and soil parameters which influence the fluid behavior in the porous media. These parameters are the dynamic viscosity, the fluid density, the surface tension, the grain-size distribution, the porosity, the intrinsic permeability, the wettability and the capillary pressure.

Fluid Dynamic Viscosity

The viscosity can be defined as the internal resistance opposing the fluid deformation or flow. This internal resistance is due to the cohesive forces within the fluid. For Newtonian fluids, a simple linear relationship exists between the shear stress and the shear rate. The basic equation of the deformation is given by:

$$\tau = \mu\gamma \tag{2.1}$$

where: τ Shear stress tensor (Pa)
 μ Fluid dynamic viscosity (Pa.s⁻¹)
 γ Shear rate tensor (s⁻¹)

On Figure 2.1, the fluid viscosity transmits the force \vec{F} applied to the upper plate, through the fluid to the lower plate in such a way that the x component of the fluid velocity linearly depends on the distance from the lower plate.

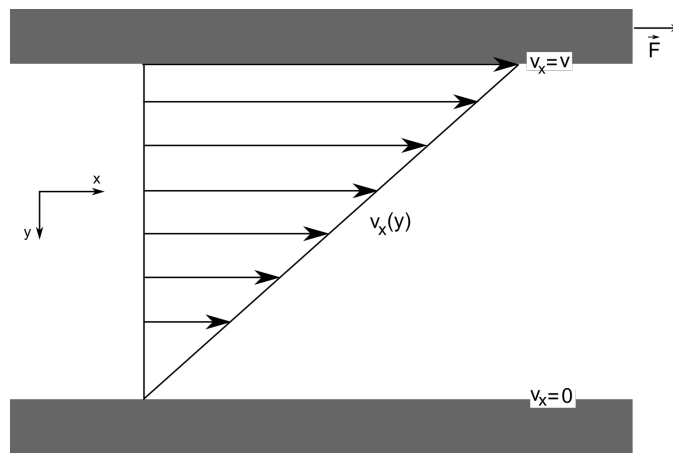


Figure 2.1: Steady-state velocity profile of a fluid entrained between two flat surfaces

The term τ can be defined as:

$$\tau = \frac{\vec{F}}{A} \tag{2.2}$$

where: \vec{F} Force required to keep the upper plate moving at constant velocity v in the x -direction (N)
 A Area of the plate in contact with the fluid (m²)

Similar to the other Newtonian fluids, the oil and water viscosities depend on temperature. A decrease in temperature causes the viscosity to rise. On the contrary, an increase in temperature causes the viscosity to be reduced. This property is important to consider when studying the oil flow in porous media and its recovery.

The typical methods to measure the dynamic viscosity are: the capillary type viscometer, the falling ball viscometer or a rotational viscometer. For liquids, the rotational viscometer is often used.

Fluid Density

The density of a fluid is the quantity of matter contained in a unit volume of the fluid. It can be expressed as a specific weight ρ which is defined as the mass of fluid per unit volume (kg.L^{-1}) or as a relative density. The relative density ρ_r is defined as the ratio of the mass density of a substance to some standard mass density. For fluids, the standard mass density is the mass density for water which occurs at 4°C and at the atmospheric pressure. The relative density is given by:

$$\rho_{ri} = \frac{\rho_i}{\rho_w} \quad (2.3)$$

where: ρ_{ri} Relative density of the fluid i (-)
 ρ_i Density of the fluid i (kg.L^{-1})
 ρ_w Density of the water at 4°C and at the atmospheric pressure (kg.L^{-1})

The relative density of a fluid is a parameter which governs its distribution in the subsurface. Most of the time oil densities are lower than water density, leading to an oil distribution mainly located above the groundwater table.

The density of a liquid is measured by simply weighing a known volume.

Surface and Interfacial Tension

Within fluids, there exist molecular attraction forces which enable the fluids to resist tensile stress (cohesion forces) and to adhere to another body (adhesive forces). Due to these forces, the molecules near the interface separating the two fluids have greater energy than molecules within the bulk phase. This excess interfacial energy makes the interface act as a membrane under tension, and when two immiscible fluids are in contact a sharp interface exists between both. This situation reflects a phenomena called interfacial tension. The total energy of the system is minimized through minimizing the interfacial area (Hillel, 1980). Therefore, the interfacial tension can be defined as the contractile tendency which exists when two immiscible liquids are in contact. One can note that the surface tension is the similar property of a liquid surface when exposed to its vapour. On Figure 2.2, the effect of the interfacial tension is to reduce the size of the sphere unless it is opposed by a sufficiently great difference between pressures p_j and p_i .

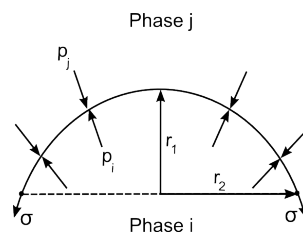


Figure 2.2: Capillary equilibrium of a spherical cap (after Defay *et al.* (1966))

The interfacial tension (σ_{ij}) between two immiscible phases i and j can be defined using the equations of Young (1805) and Laplace (1806) as follows (Adamson, 1982):

$$p_j - p_i = \sigma_{ij} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \quad (2.4)$$

where: p_j and p_i Pressure from each phase i and j (Pa)
 r_1 and r_2 Principal radii of curvature (m)

Introducing the mean radius of curvature r_m defined by:

$$\frac{1}{r_m} = \frac{1}{2} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \quad (2.5)$$

The Young-Laplace equation (2.4) becomes:

$$p_i - p_j = \frac{2\sigma_{ij}}{r_m} \quad (2.6)$$

Interfacial tension is an important parameter which governs the fluid movements in the soil through the capillary forces.

The interfacial tension can be measured by four main approaches (Adamson *et al.*, 1967):

- The Maximum Bubble Pressure Method.
- The Detachment Methods which includes the Drop Weight Method, the Ring Method, the Wilhelmy Slide Method.
- The methods based on the Shape of Static Drops or Bubbles which includes the Pendant Drop Method, the Sessile Drop or Bubble Methods.
- The dynamic methods which includes the Flow Methods, the Capillary Waves Method.

The Pendant Drop method is typically used for interfacial tension measurement. The general procedure is to form the drop under conditions such that it is not subject to disturbances and then to measure its dimensions or profile from a photograph or with digital image processing of video images (Adamson *et al.*, 1967). The typical shape of a pendant drop is presented in Figure 2.3.

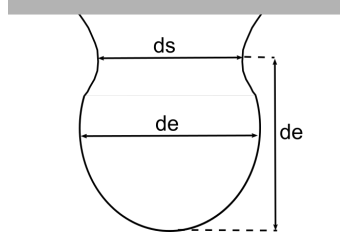


Figure 2.3: Shapes of a Pendant Drop

The analytical solution involved to define a shape-dependant quantity as $S = d_s/d_e$, d_e is the equatorial diameter and d_s is the diameter measured at a distance d_e up from the bottom of the drop. The surface tension or interfacial tension between the fluid i and j is given by (Adamson *et al.*, 1967):

$$\sigma_{ij} = \frac{\Delta p g d_e^2}{H} \quad (2.7)$$

with:

$$H = -\beta(d_e/r_m)^2 \quad (2.8)$$

where: β	Dimensionless parameter called Bond Number	(-)
b	Radius of curvature	(m)
g	Gravitational acceleration	(m.s ⁻²)

The relationship between the shape-dependent quantity H and the experimentally measured quantity S was originally determined empirically. The current approach involves computer matching of the entire drop profile to a best fitting theoretical curve. In this way the entire profile is used, rather than just d_s and d_e , so that precision is increased.

Grain Size Distribution

Soil consists of particles with various shapes and sizes which determine along with other parameters like grain arrangements and compaction, the soil porosity and intrinsic permeability. The grain-size distribution is determined as the distribution of the soil particles around the mean size. These distributions allow the classification of unconsolidated geological materials. Table 2.1 presents a commonly employed system to classify soil based on the size of the soil particles.

Table 2.1: Soil classification based on particle size (Morris and Johnson, 1967)

Materials	Particle size (mm)
Clay	0.004
Silt	0.004 - 0.062
Very fine sand	0.062 - 0.125
Fine sand	0.125 - 0.25
Medium sand	0.25 - 0.5
Coarse sand	0.5 - 1.0
Very coarse sand	1.0 - 2.0
Very fine gravel	2.0 - 4.0
Fine gravel	4.0 - 8.0
Medium gravel	8.0 - 16.0
Coarse gravel	16.0 - 32.0
Very coarse gravel	32.0 - 64.0

This parameter is easily obtained by sifting the soil and gives a good indication of the heterogeneity of the media.

Porosity

The porosity is defined as the ratio of pore volume to bulk volume and may be expressed either as a percent or a fraction. In equation form the porosity can be defined as:

$$\phi = \frac{\text{Pore Volume}}{\text{Bulk Volume}} = \frac{\text{Bulk Volume} - \text{Grain Volume}}{\text{Bulk Volume}} \quad (2.9)$$

where: ϕ Porosity (-)

Several types of porosity exist. In this study, the total or absolute porosity (ϕ_{tot}) and the effective porosity (ϕ_{eff}) are considered. The total porosity is the ratio of all the pores spaces in a soil to the bulk volume of the soil. The effective porosity is the ratio of the interconnected void spaces to the bulk volume. Thus, only the effective porosity contains the fluid that can flow in the subsurface. In this manuscript, the term "porosity" refers to the effective porosity. Considering unconsolidated material, the porosity depends on the shape and arrangement of individual particles, distribution by size and degree of concentration and compaction. Porosities range from near zero to more than 50%, depending upon the above factors and the type of material.

Porosity can be measured by direct method, optical method, imbibition method, mercury injection method, gas expansion method and density methods. The density methods depend

on determining the bulk density of a sample and the density of the solids in the sample. Since the mass of a porous medium resides entirely in the solids matrix, we have the following (Dullien, 1979):

$$m = \rho_s V_s = \rho_b V_b \quad (2.10)$$

where: m	Mass of the sample	(kg)
ρ_s	Density of the solid in the sample	(kg/m ³)
ρ_b	Bulk density of the sample	(kg/m ³)
V_s	Volume of solid	(m ³)
V_b	Volume of the sample	(m ³)

By definition of the porosity ϕ , there follows that:

$$\phi = 1 - (V_s/V_b) = 1 - (\rho_b/\rho_s) \quad (2.11)$$

The density method yields the total porosity. To obtain the effective porosity, a usual approach is the imbibition method. Immersing the porous sample in a preferentially wetting fluid under vacuum for a sufficiently long time will cause the wetting fluid to imbibe into all the connected pore space. The sample is weighted before and after the imbibition. These two weights, coupled with the density of the fluid, permit calculation of the pore volume. When the sample is completely saturated with the wetting fluid, a volumetric displacement measurement in the same wetting fluid gives directly the value of the bulk volume of the sample. From the pore volume and the bulk volume, the porosity can be directly calculated using Equation 2.9 (Dullien, 1979).

Intrinsic Permeability

The permeability of a soil defines its ability to transmit a fluid. This is a property only of the medium and is independent of the fluid properties. To avoid confusion with hydraulic fluid conductivity, which includes the properties of fluid, an intrinsic permeability k may be expressed as:

$$k = \frac{K_i \mu_i}{\rho_i g} \quad (2.12)$$

where: k	Intrinsic permeability	(m ²)
K_i	Hydraulic fluid conductivity	(m.s ⁻¹)
μ_i	Fluid i dynamic viscosity	(Pa.s ⁻¹)
ρ_i	Fluid i density	(kg.m ⁻³)
g	Gravitational acceleration	(m.s ⁻²)

Wettability

The wettability is a parameter which depends on both fluid and soil characteristics. The same fluid may act as a wetting fluid in contact with a soil and as a non-wetting fluid in contact to another soil. For multiphase condition, a fluid may be the wetting or the non-wetting fluid depending on the other fluids present in the porous media.

When a fluid enters the soil, along lines of contact of the interface between a fluid and a solid, the interface makes a contact angle θ_c . The phase that shows greater preference towards contact with the solid is called the wetting fluid, and the phase that shows less preference is called the non-wetting fluid. For a wetting phase $\theta_c < 90^\circ$ and for a non-wetting phase $\theta_c > 90^\circ$, as shown Figure 2.4.

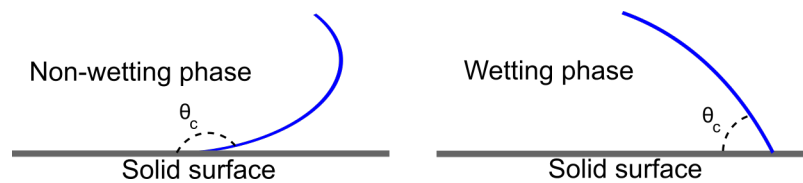


Figure 2.4: Wettability and contact angle

In the porous medium, the wetting fluid tends to coat the grain and the non-wetting fluid is expelled towards the interior of the void space. In Figure 2.5, oil is the non-wetting fluid and water is the wetting fluid.

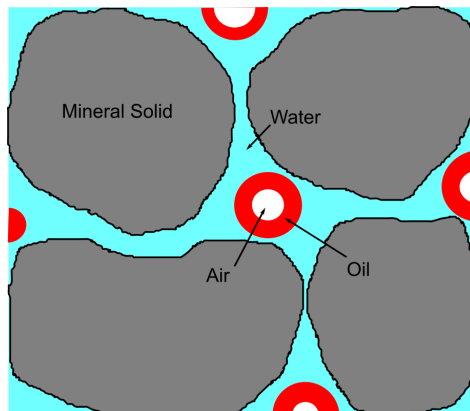


Figure 2.5: Illustration of typical distribution of fluids in the saturated zone of a porous media (from Mayer and Hassanizadeh (2005))

The contact angle provides the only direct and unambiguous specification of wettability. Contact angles, however, cannot be measured within a natural porous media. The test is conducted with flat, nonporous samples prepared of the material constituting the porous medium (Dullien, 1979). In addition, according to Brown *et al.* (1956) the concept of a contact angle is not representative in the case of a reservoir rock because this is often composed of many different minerals, each with a different surface chemistry and a different capacity

to adsorb surface active materials from reservoir fluids. For the same reason, this statement would also apply to fluids in the shallow aquifers. A typical approach is to use the extent and rate of imbibition to measure wetting preference (Bobek *et al.*, 1958). In this context, imbibition refers to a process in which a wetting fluid displaces a non-wetting fluid in a porous medium by capillary forces alone. Studies have been conducted to correlate contact angles with imbibition rate behavior for porous media (Gatenby and Marsden, 1957; Morrow and Mungan, 1971). For usual field conditions with mineral solid soil, the water is the wetting fluid, the air is the non-wetting fluid and the oil has the intermediate wettability. It means that the oil is usually the non-wetting fluid when in contact with water and the wetting fluid when in contact with air. The wettability order has a key influence on the distribution of the fluids in the porous media. When three phases are present, the water usually coats the grain and the oil forms a film around the air present in the middle of the void space.

Capillary Pressure

The left side term of Equation 2.6 is the pressure difference across the interface between the phases and is called the capillary pressure. The capillary pressure is the excess of the pressure in the non-wetting phase over the wetting phase. At the capillary scale, this excess results in capillary rise phenomena trying to minimize the free energy of the system at the equilibrium. The capillary pressure can be calculated using the Young-Laplace equation as follows (Adamson, 1982):

$$p_c = \frac{2\sigma_{ij} \cos \theta_c}{r_m} \quad (2.13)$$

where: p_c Capillary pressure (Pa)

The capillary pressure is determined experimentally by measuring the difference between the pressures in the two phases at the point of interest. For a air/water system, the measurement is performed with a "porous cup tensiometer". This device gives directly the "capillary pressure head" or "suction head", defined as follows:

$$h_c = P_c / \rho_w g \quad (2.14)$$

where: p_c Capillary pressure (Pa)
 ρ_w Water density (kg.m⁻³)
 g Gravitational acceleration (m.s⁻²)

The capillary pressure is a function of the fluid saturation (proportion of a fluid in the porosity volume). The capillary pressure in a porous medium is an increasing function of the nonwetting phase saturation or, alternately, a decreasing function of the wetting phase saturation. Figure 2.6 shows typical capillary pressure curve, where S_{wr} is the residual water saturation and S_{or} is the residual oil saturation. Both S_{wr} and S_{or} are dimensionless parameters.

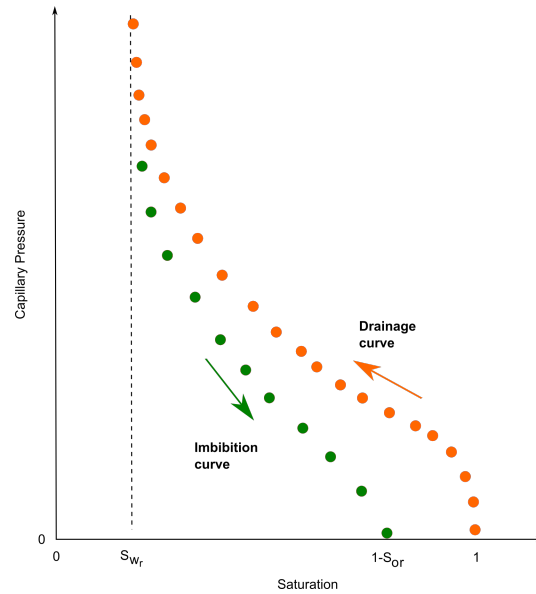


Figure 2.6: Soil capillary pressure curve showing primary drainage and imbibition (Charbeneau, 2007)

One can note that imbibition and drainage reproduced several times on the same porous medium sample leads to slightly different drainage and imbibition curves. This phenomena is due to the capillary hysteresis which means that the value of the capillary pressure function may have an infinity of different values between an upper and a lower bound, depending on wetting history of the medium. It has generally two causes: hysteresis of contact angle and pore structure effect.

Considering the water as the wetting fluid, and the capillary pressure and saturation relation, the above residual water saturation S_{wr} (or "irreducible saturation") is defined as the reduced volume of water retained at the highest capillary pressures where the water phase saturation appears to be independent of further increases in the externally measured capillary pressure. The residual oil saturation, S_{or} is defined as the reduced volume of oil that is entrapped when the externally measured capillary pressure is decreased from a high value to zero.

For a single phase system, the laboratory methods for measuring the relationship $P_c = P_c(S_w)$, where S_w is the saturation of wetting phase of porous media may be divided into two groups:

- (1) Static method based on the establishment of successive states of hydrostatic equilibrium.
- (2) Dynamic methods based on the establishment of successive states of steady flow.

2.1.2 Fluid Distribution and Mobility in Porous Medium

This part presents the parameters which are measured to specify the fluid distribution and mobility in the porous media. The fluid distribution is characterized by the vertical and horizontal gradients of fluid saturations, whereas the fluid mobility is mainly specified by

its hydraulic conductivity which may be expressed as fluid transmissivity. In multiphases condition, the hydraulic fluid conductivity will depend on the relative permeability of each fluid.

Fluid Saturation in Porous Media

The total saturation of fluid phase i is defined as:

$$S_i = \frac{\text{Volume of fluid phase } i \text{ in the sample}}{\text{Total accessible pore volume in the sample}} \quad (2.15)$$

where: S_i Total saturation of fluid phase i (-)

If we consider a two-phase system with oil and water, the effective water saturation represents the saturation which can flow in the porous media, and is defined as:

$$S_{e[w]} = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{or}} \quad (2.16)$$

where: S_w Total water saturation (-)
 S_{wr} Residual water saturation (-)
 S_{or} Residual oil saturation (-)

The total effective saturation $S_{e[t]}$ (or effective liquid saturation) is defined as:

$$S_{e[t]} = \frac{S_w + S_o - S_{wr} - S_{or}}{1 - S_{wr} - S_{or}} \quad (2.17)$$

where: S_o Total oil saturation (-)

At field scale, the fluid saturation measurements is only valid for the limited area from where the sample has been collected. Often, saturations through the area of concern are estimated from the oil thickness measured in the monitoring well using the theoretical models (Lenhard and Parker, 1990; Farr *et al.*, 1990). In an air/water system where only two phases are present, the Brooks and Corey (1964) and Van Genuchten (1980) models are widely used to link the water saturation to the capillary pressure head.

The Brooks and Corey parametric model gives:

$$S_{e[w]} = \left(\frac{h_d}{h_c} \right)^\lambda; h_c \geq h_d \quad (2.18)$$

$$S_{e[w]} = 1; h_c < h_d \quad (2.19)$$

where:	\$S_{e[w]}\$	Water effective saturation	(-)
	\$h_d\$	Displacement pressure head	(m)
	\$h_c\$	Capillary pressure head	(m)
	\$\lambda\$	Brooks and Corey pore size distribution parameter	(-)

and, the Van Genuchten model gives:

$$S_{e[w]} = [1 + (\alpha h_c)^n]^{-m} \tag{2.20}$$

where:	\$\alpha\$	Van Genuchten parameter	(m ⁻¹)
	\$n\$	Van Genuchten parameter	(-)
	\$m = 1 - 1/n\$		

In an oil/water system, three phases are present in the porous media. Therefore, interfaces between several pairs of immiscible fluids are occurring. As measurements of capillary pressure curves are made for a single fluid-pair system, the parameters that have been determined for one fluid system need to be scaled. The parameter \$\alpha\$ is directly associated with the capillary pressure head, while the parameter \$n\$ is associated with the pore size distribution. It is assumed that the pore size distribution does not change for different fluid systems. Therefore, \$\alpha\$ is the only parameter which needs to be scaled. From Equation 2.13, it appears that the scaling relationships should include the surface tension and contact angle ratios. Assuming that the \$\alpha\$ value was obtained for an air/water system, the appropriate scaling relationships for the oil/water and oil/air system are (Charbeneau, 2007):

$$\alpha_{ow} = \left(\frac{\sigma_{aw}}{\sigma_{ow}} \right) \alpha_{aw} \tag{2.21}$$

$$\alpha_{ao} = \left(\frac{\sigma_{aw}}{\sigma_{ao}} \right) \alpha_{aw} \tag{2.22}$$

where:	\$\sigma_{ij}\$	Interfacial tension between the phases i and j	(N.m ⁻¹)
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Considering vertical equilibrium conditions, the fluid elevations in the monitoring wells can be combined with the capillary pressure curve models to determine the oil saturation distribution within the formation (Farr *et al.*, 1990; Lenhard and Parker, 1990). Under equilibrium conditions between fluids in a well and those within the formation, all the variable values shown in Figure 2.7 are determined by the oil distribution in the formation.

For an incompressible fluid, the relative hydrostatic pressure equations for oil and water at the elevation \$z\$ take the following form (Charbeneau, 2003):

$$p_o(z) = p_o(z^*) - \rho_o g(z - z^*) \tag{2.23}$$

$$p_w(z) = p_w(z^*) - \rho_w g(z - z^*) \tag{2.24}$$

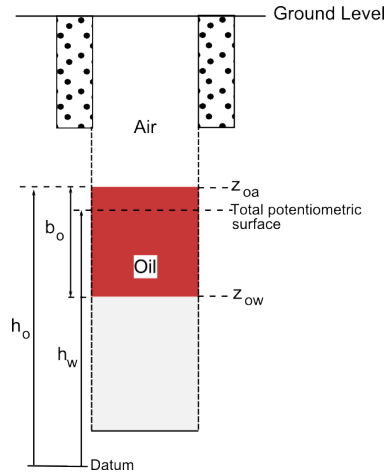


Figure 2.7: Fluid elevation within an oil monitoring well (Charbeneau, 2007)

where: z^* Reference elevation (m)
 ρ_o Oil density ($\text{kg}\cdot\text{m}^{-3}$)

Using Equations (2.23) and (2.24), under conditions of vertical equilibrium, the capillary pressure between oil and water is given by:

$$p_{c(ow)}(z) = p_{c(ow)}(z^*) + (\rho_w - \rho_o)g(z - z^*) \quad (2.25)$$

At the oil/water interface elevation (z_{ow}), the capillary pressure is zero (Figure 2.8).

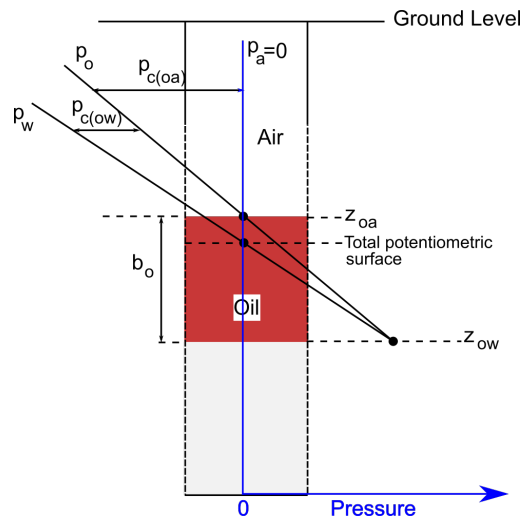


Figure 2.8: Capillary pressure distribution in the presence of oil (Charbeneau, 2007)

Therefore, conventionally z_{ow} is taken as the reference elevation. Equation (2.25) becomes:

$$p_{c(ow)}(z_{ow}) = (\rho_w - \rho_o)g(z - z_{ow}) \quad (2.26)$$

In the same way, the oil/air capillary pressure is given by:

$$p_{c(oa)}(z_{ow}) = \rho_o g(z - z_{ow}) \quad (2.27)$$

Combining Equations (2.14), (2.26) and (2.27) gives:

$$h_{c(ow)} = \frac{p_{cow}}{\rho_w g} = (1 - \rho_r)(z - z_{ow}) \quad (2.28)$$

and,

$$h_{c(oa)} = \frac{p_{coa}}{\rho_w g} = \rho_r(z - z_{oa}) \quad (2.29)$$

In the Equations (2.28) and (2.29), the density ratio ρ_r is defined by $\rho_r = \rho_o/\rho_w$.

Leverett *et al.* (1941) suggested that within a two-phase system, i) the capillary pressure between the water and oil phase depends only on the water saturation, while ii) the capillary pressure between the oil and air phases depends on the total liquid saturation. Using Equations (2.20), (2.28), and (2.29), it gives:

$$S_{e[w]}(z) = (1 + (\alpha_{ow}(h_{c(ow)}))^n)^{-m} \quad (2.30)$$

and,

$$S_{e[t]}(z) = (1 + (\alpha_{oa}(h_{c(oa)}))^n)^{-m} \quad (2.31)$$

Equations (2.30) and (2.31) are often written in the form:

$$S_{e[w]}(z) = (1 + (\alpha'_{ow}(z - z_{ow}))^n)^{-m} \quad (2.32)$$

and,

$$S_{e[t]}(z) = (1 + (\alpha'_{oa}(z - z_{oa}))^n)^{-m} \quad (2.33)$$

Equations (2.34) and (2.35) introduce new scaling factors that take into account surface tension and buoyancy effects:

$$\alpha'_{ow} = (1 - \rho_r) \frac{\sigma_{aw}}{\sigma_{ow}} \alpha \quad (2.34)$$

and,

$$\alpha'_{oa} = \rho_r \frac{\sigma_{aw}}{\sigma_{oa}} \alpha \quad (2.35)$$

The effective oil saturation $S_{e[o]}$ can be estimated from the Equations (2.30) and (2.31), using:

$$S_{e[o]}(z) = S_{e[t]}(z) - S_{e[w]}(z) \quad (2.36)$$

From there, one can estimate the fluid saturations in the porous media at the elevation z knowing the interface elevations in the monitoring wells when the vertical equilibrium condition is present. All these saturation models proposed by Lenhard and Parker (1990) and

by Farr *et al.* (1990) rely on the assumptions of vertical equilibrium and homogenous porous media through the interval of concern.

Hydraulic Conductivity

The hydraulic conductivity reflects the capacity of a fluid to move through a porous medium. To introduce the hydraulic conductivity, it is first necessary to define the Darcy's law. Considering Figure 2.9 which represents a sand column filled by water, the total energy heads above a datum plane may be expressed by the energy equation:

$$\frac{p_1}{\gamma_w} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma_w} + \frac{v_2^2}{2g} + z_2 + h_L \quad (2.37)$$

where: p	Pressure	(Pa)
γ_w	Water specific weight	(kg.m^{-3})
v	Velocity of flow	(m.s^{-1})
g	Gravitational acceleration	(m.s^{-2})
z	Elevation	(m)
h_L	Head loss	(m)

Because velocities in porous media are usually low, velocity heads may be neglected without appreciable error. Hence, the head loss becomes:

$$h_L = \left(\frac{p_1}{\gamma_w} + z_1 \right) - \left(\frac{p_2}{\gamma_w} + z_2 \right) \quad (2.38)$$

The head loss is therefore, independent of the inclination on the cylinder.

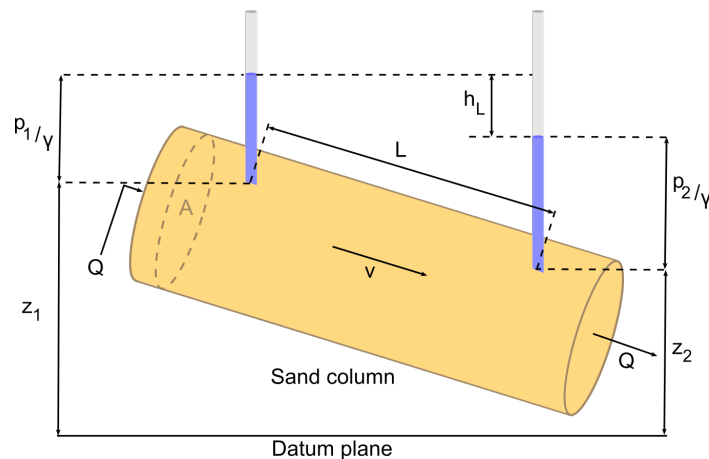


Figure 2.9: Pressure distribution and head loss in flow through a sand column (after Todd (1980))

Darcy (1856) showed from his work that the proportionalities $Q \sim h_L$ and $Q \sim 1/L$ exist. Introducing a proportionality constant K_w leads to the equation:

$$Q = -K_w A \frac{dh}{dl} \quad (2.39)$$

where: Q Volumetric flow rate of water (m³.s⁻¹)
 K_w Hydraulic conductivity (m.s⁻¹)
 dh/dl Hydraulic gradient (-)

or

$$v = \frac{Q}{A} = -K_w \frac{dh}{dl} \quad (2.40)$$

where: v Darcy velocity or specific discharge (m.s⁻¹)

The negative sign indicates that the flow of water is in the direction of decreasing head. Should the porous media be saturated with a fluid i instead of water, then one can talk about hydraulic fluid conductivity and replace the term K_w in Equations (2.39) and (2.40) by K_i .

The measurement of the hydraulic conductivity in a laboratory is usually performed on core samples. Based on the approach presented Figure 2.9, the measurement is performed at several steady flow rates. For each flow rate, the head loss is measured and the hydraulic conductivity is calculated from the Darcy's law using Equation 2.39.

Transmissivity

The transmissivity T may be defined as the rate at which a fluid is transmitted through a unit width of aquifer under a unit hydraulic gradient. The transmissivity is defined as:

$$T_i = K_i b \quad (2.41)$$

where: T_i Transmissivity of the fluid i (m².s⁻¹)
 b Thickness crossed by the fluid i (m)
 K_i Hydraulic conductivity of the fluid i (m.s⁻¹)

Fluids Relative Permeability

When two or more fluids are simultaneously present in a porous medium, they will compete for the pore space. As a result, the hydraulic conductivity for each fluid will be smaller than the hydraulic conductivity when only one of these fluids is present. This leads to the concept of relative permeability, which is defined as the ratio of the hydraulic conductivity of a phase at a given saturation to the hydraulic conductivity of the same phase when its saturation is

1. Considering a two-phase system with oil and water present in the porous medium, the oil relative permeability k_{ro} is defined as

$$k_{ro}(S_o, S_w) = \frac{K_o(S_o)}{K_o(S_o=1)} \quad (2.42)$$

where: k_{ro} Oil relative permeability (-)
 K_o Hydraulic Oil Conductivity (m.min⁻¹)

Relative permeability functions can be determined in the laboratory on porous medium cores using various direct and indirect techniques (Sale and McWhorter, 2001). Direct techniques involve imposing steady-state flows of both phases on the core. By measuring the saturations and the pressure differences in the phases across the core, the hydraulic conductivities of each phase can be determined by applying Darcy's law. By varying the flow rates of the phases, individual points on the relative permeability curves can be determined. Indirect methods involve performing dynamic displacement experiments while measuring responses of relevant variables with time at various locations within the core. Laboratory measurement of the relative permeability is elaborate and tedious to perform (Mayer and Hassanizadeh, 2005). Therefore, predictive models based on the capillary pressures have been proposed.

Burdine *et al.* (1953) and Mualem (1976) model equations are commonly used. Parker *et al.* (1987) combined the Burdine and Mualem solutions with the Van Genuchten (1980) and Brooks and Corey (1964) parametric models [Equations (2.18) and (2.20)] to determine the oil relative permeability.

For a two-phase system, the oil relative permeability equation combining Van Genuchten / Burdine solution is (Charbeneau, 2007):

$$k_{ro}(S_w, S_o) = S_o^2 \left[\left(1 - S_{e[w]}^{(1/m)}\right)^m - \left(1 - S_{e[t]}^{(1/m)}\right)^m \right] \quad (2.43)$$

The Van Genuchten / Mualem solution is:

$$k_{ro}(S_w, S_o) = \sqrt{S_o} \left[\left(1 - S_{e[w]}^{(1/m)}\right)^m - \left(1 - S_{e[t]}^{(1/m)}\right)^m \right]^2 \quad (2.44)$$

and, the Brooks and Corey / Burdine solution is:

$$k_{ro}(S_w, S_o) = S_o^2 \left[\left(S_{e[t]}\right)^{\frac{\lambda+2}{\lambda}} - \left(S_{e[w]}\right)^{\frac{\lambda+2}{\lambda}} \right] \quad (2.45)$$

In a two-phase system, the hydraulic oil conductivity depends on the oil relative permeability, as follows:

$$K_o(S_w, S_o) = \frac{\rho_o g k k_{ro}}{\mu_o} \quad (2.46)$$

where: K_o Oil permeability (m.s⁻¹)
 k Intrinsic Permeability (m²)
 μ_o Oil dynamic viscosity (Pa.s⁻¹)

As shown in this section, several parameters will influence the oil distribution and migration in the subsurface. The oil mobility is quantified by its hydraulic conductivity or its transmissivity through a defined portion of an aquifer. The hydraulic conductivity measurement at the laboratory scale gives an indication on how fast the oil moves through a core sample but is not representative of the field conditions. An undisturbed core sample can be difficult and tedious to obtain and represents only a very small portion of the studied area. Considering the heterogeneity of soils, it is obvious that to support laboratory indicative values of the hydraulic oil conductivity, field measurements are necessary.

2.2 Oil Mobility Estimation at Field Scale

The understanding of the oil nature, distribution and mobility in porous media is a key step for defining the optimal recovery design. The typical approach is to first investigate the nature, the extent and the distribution of the oil contamination, before estimating the oil mobility. The oil extent and distribution can be determined by combining screening tools (e.g. Light Induced Fluorescence technique) with more conventional methods (e.g. soil core borings, wells implementation). The screening tool gives a qualitative understanding of the geology along with the oil vertical and horizontal distribution. The soil core borings and the wells are implemented to confirm and quantify the oil distribution and soil parameters, inferred by the screening tool. The analysis of undisturbed core borings allows the measurement of the moisture content of the soil, the porosity, the oil saturation at depth and the determination of grain size distribution. From the boreholes, one can confirm that the oil is present as a free phase, measure the oil thickness after equilibration is reached and take product samples to define the physical properties of the free oil phase. Finally, the analysis of the geological log and of the well configuration data allows the identification of possible unconfined, confined or perched LNAPL conditions. At the end of this investigation step, the site specific conditions (i.e.: soil properties, geological context, hydrogeological conditions), the horizontal and vertical distribution of the oil and its nature are usually defined.

The following investigation phase is focused in defining how the oil is moving in the soil. This understanding is critical to select the cleanup approach, to design the extraction method and to anticipate the performance and duration of the oil recovery project. The parameter related to the oil lateral mobility through the soil is the transmissivity. This parameter is related to the bulk ability of oil to move through porous media under mixed saturation conditions (Beckett and Huntley, 2015a). At the laboratory scale, the oil transmissivity may be estimated from the hydraulic oil conductivity determined from undisturbed soil core borings (Section 2.1.2). The hydraulic conductivities of each phases (water and oil) are determined by imposing steady-state flow of both phases on the core. Considering the field heterogeneity and the difference in vertical oil saturation, the use of the oil transmissivity determined from a core sample may lead to unrealistic values when used for the interpretation of the mobility at the field scale. Therefore, to get a better understanding of the oil mobility at the field scale, the prevalent approach developed over the last decades is the bail-down test. This section presents the purpose of a bail-down test performed in a two-phase system and the theory to interpret these tests.

2.2.1 Bail-down Test Protocol and Pre-Analysis Diagnostic

The bail-down test 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). Within the past 35 years, bail-down tests have been performed in the environmental industry to gather information about site-specific subsurface conditions in a two-phase system (Yaniga and Demko, 1983). The bail-down test consists of removing the free phase product from a well within a short period of time, minimizing the quantity of water removed so as not to disturb the oil/water interface. To be applicable, the test should be performed in wells showing more than 30 cm of product (Kolhatkar *et al.*, 2000). A bail-down test has three parts. First, initial measurements are taken to define the pre-test conditions. Second, free product is rapidly removed from the well. Third, free product recovery is monitored. A schematic representation of a bail-down test for a two-phases system is presented in Figure 2.10.

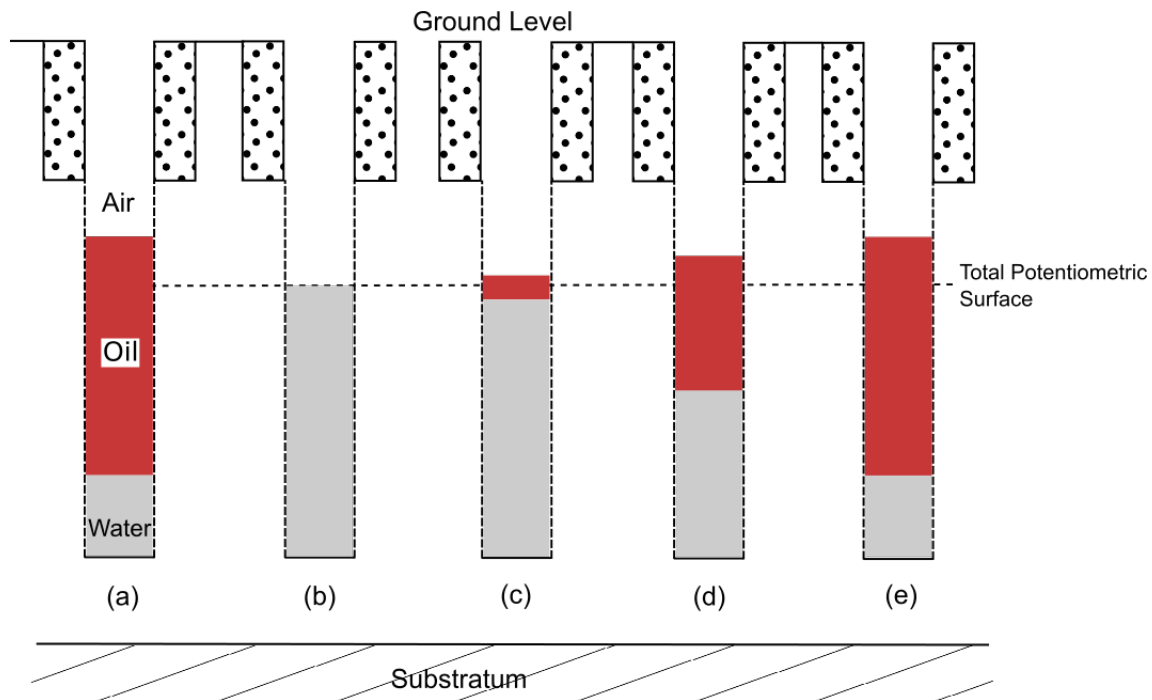


Figure 2.10: Schematic view of a bail-down test in a two-phase system. (a) Pre-test conditions; (b) time 0 after oil removal; (c), (d) and (e) oil recovery over time in a well

These three parts of the test are further described below (ASTM Standard E2856-13, Hampton (2003)).

- The typical field data (date, time, location, well number, field personnel participating, type of material used) are recorded. An example of bail-down test data form is presented in Annex A. Then, measurement of the oil/air and oil/water interface levels

at equilibrium conditions using an interface probe, is performed to define the pre-test conditions.

- Removal of the entire oil thickness from the well, as quickly as possible. This oil extraction is usually performed using a peristaltic pump to remove only the oil phase. The goal is to pump only free product, which is achieved by maintaining the end of the pump intake tube in the free product zone. The pumping is ceased when water is visible in the intake tube. As the objective is to remove rapidly the free product, one can use two peristaltic pumps to increase the flow rate. One alternative to the peristaltic pump for product removal is to use a bailer. In this case, the preferred model is a clear acrylic bailer, to see the free oil, with a large bottom opening. However, with this approach it is difficult to get the total amount of oil removed.
- Monitoring of the oil/air and oil/water interface levels during the time the oil thickness in a well recovered to (or nearly to) pre-test levels. This monitoring is most of the time performed with a manual interface probe. The standard approach is to measure the interface levels at closely-spaced time intervals soon after the oil extraction. Then, measurements of the interface levels is performed at greater time intervals. The definition of the appropriate time interval is closely related to how fast the oil is flowing back to the well. For lubricant oil, it may take few days whereas, considering a low viscosity product like diesel fuel in a fairly permeable subsurface condition, the pre-test conditions may be reached in a few hours. One can mention here, that if free product recovers too fast to be accurately tracked by manual readings, an automatic method could be used. It is possible by placing three automatic pressure probes in the well, as shown Figure 2.11. However, this approach is not often used.

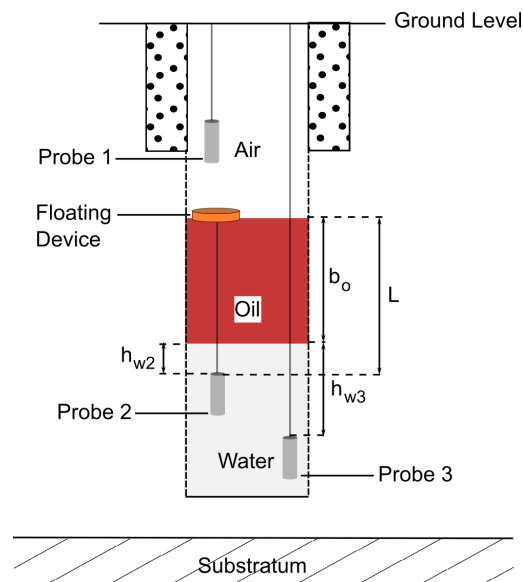


Figure 2.11: Schematic view of automatic probe system for interfaces levels measurement during a bail-down test

The probe 1 gives the atmospheric pressure. For the probes 2 and 3, the measured pressures are defined as:

$$p_2 = p_{atm} + h_{w2}\rho_w g + b_o\rho_o g \quad (2.47)$$

and,

$$p_3 = p_{atm} + h_{w3}\rho_w g + b_o\rho_o g \quad (2.48)$$

where: p_2 and p_3	Pressures measured with probes 2 and 3	(Pa)
h_{w2}	Height between probe 2 and the oil/water interface	(m)
h_{w3}	Height between probe 3 and the oil/water interface	(m)
b_o	Oil thickness	(m)
ρ_w	Water density	(kg.m ⁻³)
ρ_o	Oil density	(kg.m ⁻³)
g	Gravitational acceleration	(m.s ⁻²)

As L , the distance between probe 2 and the oil/air interface is known, one can calculate b_o and h_{w3} as follows:

$$b_o = \frac{(p_2 - p_{atm})/g - L\rho_w}{(\rho_o - \rho_w)} \quad (2.49)$$

and,

$$h_{w3} = \frac{(p_3 - p_{atm})/g - b_o\rho_o}{\rho_w} \quad (2.50)$$

Using Equations (2.49) and (2.50), the interface levels are determined for each time step. At the end of the test, the key field collected data are the interface levels before the test which defines the pre-test conditions, and the interface level variations over the time after the oil has been bailed out. The interface level variations over the time is usually plotted as shown Figure 2.12.

Before estimating the oil transmissivity, it is necessary to plot the well drawdown versus the well recharge. The curve is used to identify whether the oil in the formation was initially in equilibrium with the oil in the well. If the oil in the well is not equilibrated with the oil in the adjacent formation, drawdown adjustment is necessary for estimating the true oil drawdown. In addition, the general shape of this relationship can be used to identify conditions with significant borehole recharge from the filter pack and as well as the condition of the oil mass (i.e.: confined, unconfined or perched).

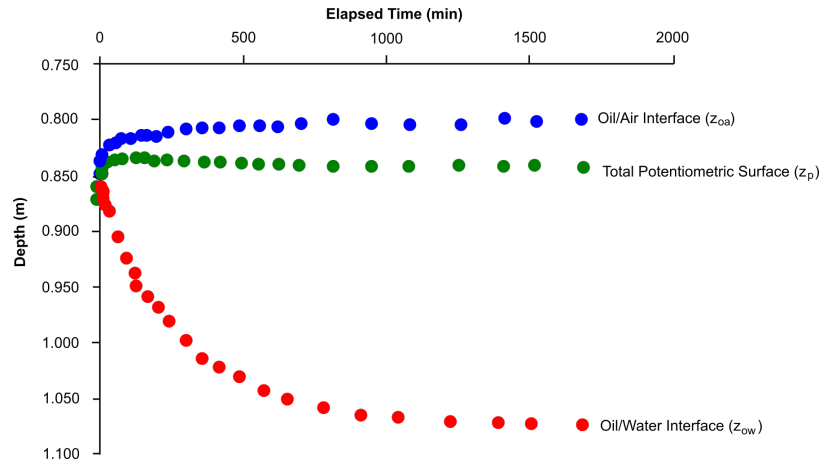


Figure 2.12: Example of interface level variations during a bail-down test

Figure 2.13 shows examples of well drawdown versus well recharge. Figure 2.13 (a) shows unconfined oil where significant well recharge from the filter pack occurred. The initial data shows large discharge which is primarily associated with the filter pack. Once the drawdown is smaller than 0.20 m, consistent linear drawdown/discharge behavior is observed. Also, the linear part of the curve does not approach zero drawdown at zero discharge. Instead, it appears that the extrapolated limit has zero discharge with an oil drawdown ($s_o = 0.06$ m). Such behavior suggests that the oil in the formation and the oil in the well were not initially in equilibrium, and that a drawdown correction of $\Delta s_o = 0.06$ m should be applied to the data before oil transmissivity analysis (Charbeneau, 2012).

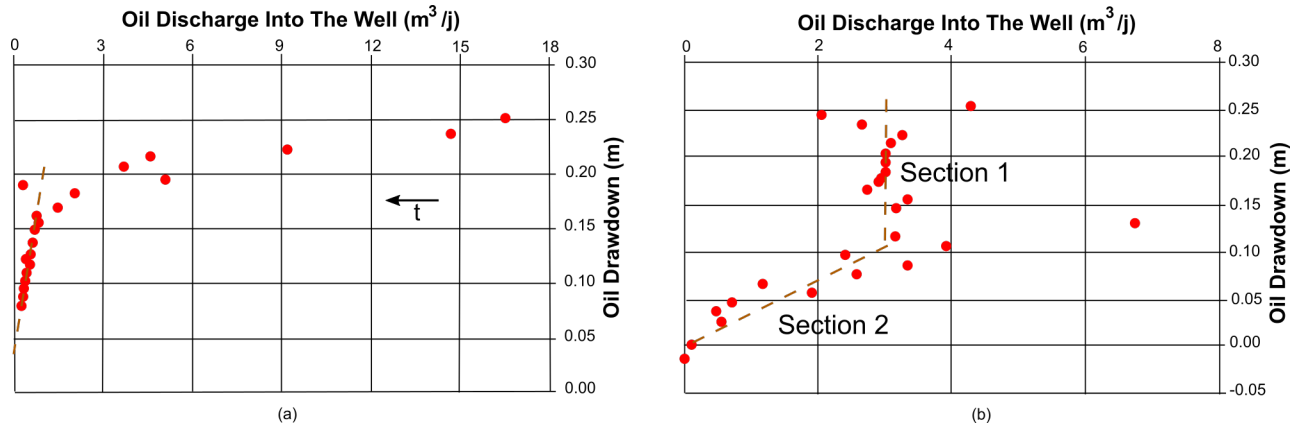


Figure 2.13: Example of oil drawdown versus oil discharge relation (Charbeneau, 2012)

Figure 2.13 (b) shows a behavior that suggests confined (or perched) oil mass condition. In this case, it represents confined conditions with the water table initially located at an elevation below the confined oil and with resulting exaggerated oil thickness in the well. Immediately following the oil removal from the well, the oil level in the well is too low, and oil discharge from the formation occurs at a constant rate while the oil drawdown is

declining (Section 1 of the curve). Once the oil column thickness within the well increases and contacts the mobile oil formation, the inflow rate is retarded and decreases at a linear rate along with the oil drawdown (Section 2 of the curve). In that case, one may analyze oil transmissivity from the constant inflow rate along with limiting oil drawdown value (about 0.1 m in this example), or one can use standard (unconfined) equations on the data from the linear drawdown/discharge part of the curve (Charbeneau, 2012). After having collected the field data and made this pre-analysis diagnostic, one can use the data set to estimate the oil transmissivity using the bail-down test theory presented in the following section.

2.2.2 Theory for Bail-Down Test Interpretation

The bail-down test (or closely-related slug test) methods have been developed originally for single-phase system, in the context of (i) contaminated aquifers, as the test method requires much less water to be extracted and treated, and (ii) field investigation of low-permeable materials. However, the bail-down test for water transmissivity estimation is rarely used because the test requires several boundary condition constraints to be met. For single-phase systems, numerous papers have detailed these constraints and described the conditions of application (Campbell *et al.*, 1990; Hyder and Butler, 1995; Brown *et al.*, 1995; Butler Jr, 1997; Halford *et al.*, 2006).

For a two-phase system, several authors suggested applying (i) traditional slug test analyses (Cooper *et al.*, 1967; Bouwer and Rice, 1976) or (ii) modified pumping test theory (Jacob and Lohman, 1952) to interpret bail-down test measurements in a well where oil was present. The three commonly used methods of bail-down test interpretation for the two-phase system are the modified Bouwer and Rice (Lundy and Zimmerman, 1996; Huntley, 2000), the modified Cooper (Beckett and Lyverse, 2002) and the modified Jacob and Lohman (Huntley, 2000) methods.

Several methods are analysed below with an emphasis on the assumptions used.

Approaches Based on the Bouwer and Rice Solution (Bouwer and Rice, 1976)

The Bouwer and Rice solution (Bouwer and Rice, 1976) is proposed for slug test performed in unconfined aquifer with completely or partially penetrating wells. This solution is applicable to single-phase systems. A slug test follows the same protocol as a bail-down test, although instead of removing a volume of water, a volume of water is injected into the well. The theory is applicable to both tests without distinction. Figure 2.14 presents the geometry and the symbols for a bail-down test performed in a single-phase system.

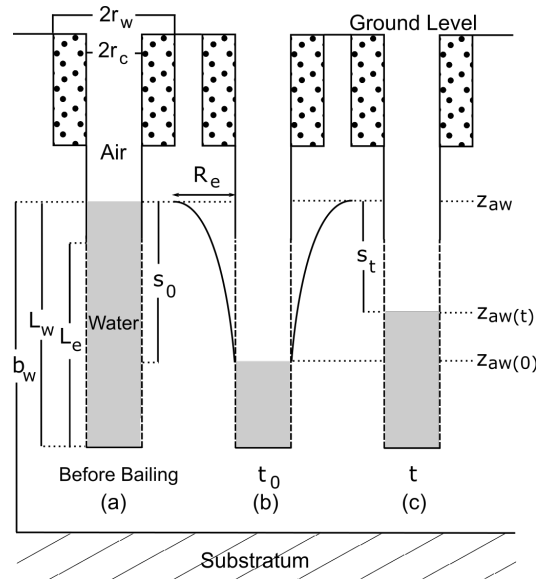


Figure 2.14: Geometry of partially penetrating wells in an unconfined aquifer a) before water bailing, b) at time t_0 and c) at time t after water bailing

The Bouwer and Rice solution (Bouwer and Rice, 1976) is based on the Thiem equation (Thiem, 1906) for steady state radial flow to a well. The water transmissivity is given by:

$$T_w = \frac{b_w r_c^2 \ln(R_e/r_w)}{2L_e} \frac{1}{t} \ln\left(\frac{s_{(0)}}{s_{(t)}}\right) \quad (2.51)$$

where:	T_w	Water transmissivity	$(\text{m}^2 \cdot \text{s}^{-1})$
	r_c	Casing Radius	(m)
	r_w	Well Radius	(m)
	R_e	Effective Well Radius	(m)
	L_e	Height of the portion of well through which water enters	(m)
	t	Elapsed time	(s)
	b_w	Aquifer thickness	(m)
	$s_{(0)}$	Air/water interface drawdown in the well at time t_0 after the water is bailed out (or introduced)	(m)
	$s_{(t)}$	Air/water interface drawdown in the well at time t after the water is bailed out (or introduced)	(m)

From the bail-down (or slug) test data set, $\log s$ is plotted versus elapsed time. $s_{(0)}$, the water drawdown at t_0 , is taken from the graph (Figure 2.15) as the intercept of the straight line fit through the data, and t and $s_{(t)}$ are the coordinates of a second point of the straight line.

One can note that the general shape of the $\log s$ versus time curve shows three distinct sections noted 1, 2 and 3 in Figure 2.15. The early data of the test with the section 1

represents the filter pack drainage, the section 2 represents the flow of oil from adjacent formation, and the section 3 corresponds to the end of the test with return to the pre-test conditions. The section 2 is therefore used for fitting the straight line.

Values of R_e , expressed as $\ln(R_e/r_w)$, were determined by Bouwer and Rice (Bouwer and Rice, 1976) with an electrical resistance network analog for different values of r_w , L_w , L_e and b_w . From this study, Bouwer and Rice derived the following empirical equations relating $\ln(R_e/r_w)$ to the geometry of the system.

If $b_w > L_w$:

$$\ln \frac{R_e}{r_w} = \left[\frac{1.1}{\ln(L_w/r_w)} + \frac{A + B \ln[(b - L_w)/r_w]}{L_e/r_w} \right]^{-1} \quad (2.52)$$

where: L_w Height of the well below the air/water interface (m)
 A and B Dimensionless coefficients (-)

If $b_w = L_w$:

$$\ln \frac{R_e}{r_w} = \left(\frac{1.1}{\ln(L_w/r_w)} + \frac{C}{L_e/r_w} \right)^{-1} \quad (2.53)$$

where: C Dimensionless coefficient (-)

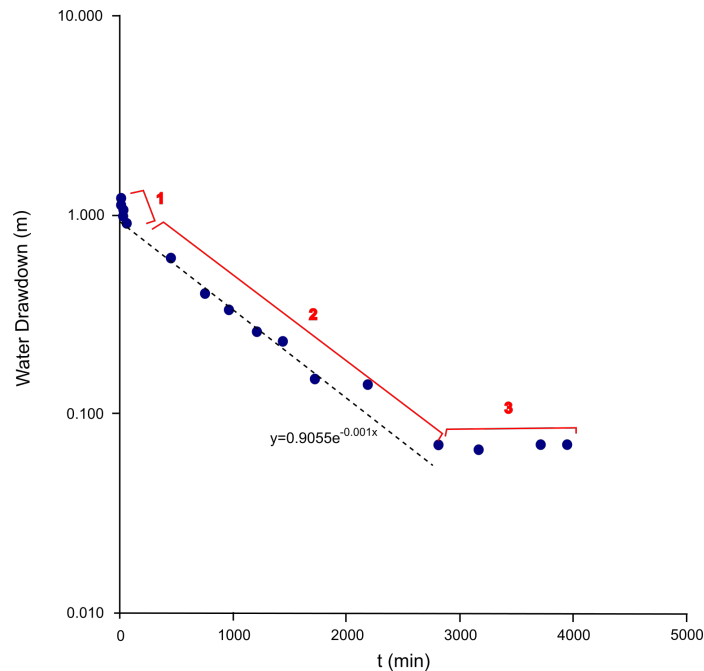


Figure 2.15: Example of the bail-down test data analysis using Bouwer and Rice

The coefficients A , B and C are functions of $\ln(L_w/r_w)$ which is determined from the well design and the groundwater level. From this value, the coefficients are given by the graph presented Figure 2.16.

Water transmissivity is calculated using the selected t and $s(t)$, the graphically determined $s_{(0)}$ and the $\ln(R_e/r_w)$ value in the Equation (2.51).

The following assumptions are common to all the methods presented in this section:

- Aquifer has infinite areal extent.
- The aquifer is homogeneous and isotropic.
- The flow above the water table in the capillary fringe can be ignored.
- The head losses as water enters the well (well losses) are negligible.
- The water head in the aquifer at the face of the well is equal to that in the well.
- At a distance R_e from the well, the change in head approaches zero.
- The volume of water is injected into or discharged from the well instantaneously.
- The water potentiometric surface is initially horizontal.

In addition to the common assumptions presented above, the Bouwer and Rice solution has been developed based on the following assumptions:

- (a.1) Water flow to the well is quasi-steady-state (storage coefficient is negligible).
- (a.2) The drawdown of the water table around the well is negligible when compared with the aquifer thickness.

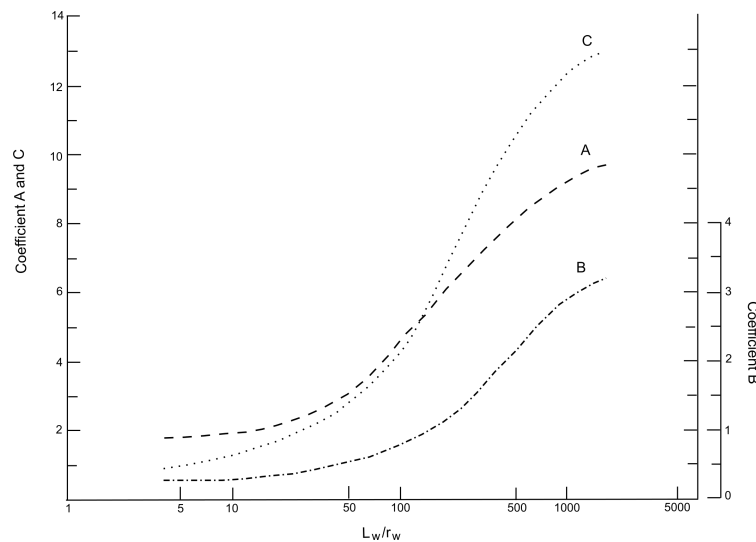


Figure 2.16: Curve relating coefficients A , B and C to $\ln(L_w/r_w)$ (Bouwer and Rice, 1976)

Bouwer and Rice solution has been modified by Lundy and Zimmerman (1996) and by Huntley (2000) to allow bail-down test interpretation in a two-phase system. In Lundy and Zimmerman solution, the oil transmissivity T_o is given by:

$$T_o = \frac{r_{ce}^2 \ln(R_e/r_w)}{2t} \ln \left(\frac{s_{o(0)}}{s_{o(t)}} \right) \quad (2.54)$$

where: T_o Oil transmissivity (m².s⁻¹)
 r_{ce} Effective casing radius (m)
 $s_{o(0)}$ Oil drawdown in the well at time t_0 after the oil is bailed out (m)
 $s_{o(t)}$ Oil drawdown in the well at time t after the oil is bailed out (m)

To account for the resaturation of the filter pack, the casing radius (r_c) should be replaced with the effective casing radius (r_{ce}) defined as (Lundy and Zimmerman, 1996):

$$r_{ce} = r_c + S_{(yo)}(r_w^2 - r_c^2) \quad (2.55)$$

where: $S_{(yo)}$ Specific yield for oil (-)

Based on laboratory tests, Lundy and Zimmerman (1996) proposed the following empirical equation to estimate the oil specific yield $S_{(yo)}$ for coarse medium:

$$S_{(yo)} = -0.0401 \ln(\mu_o) + 0.227 \quad (2.56)$$

In Huntley solution, the oil transmissivity T_o is given by:

$$T_o = \frac{r_{ce}^2 \left(\frac{1}{1-\rho_{ro}} \right) \ln(R_e/r_w)}{2t} \ln \left(\frac{s_{o(0)}}{s_{o(t)}} \right) \quad (2.57)$$

Both solutions are directly derived from the Bouwer and Rice approach. Therefore, in addition to the common assumptions already presented, the assumptions and boundary requirements which make valid the analytical solution proposed by Bouwer and Rice are applied here in the following way (Beckett and Huntley, 2015b):

- (b.1) Oil return flow is quasi-steady-state.
- (b.2) The oil drawdown initiated by the oil removal around the well being relatively small when compared with the thickness of the oil saturated layer.

To allow the oil drawdown calculation, both Lundy and Zimmerman and Huntley have made simplifying assumptions. 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 and the changes in oil thickness are assumed to represent changes in oil head (b.3).

Huntley makes the assumption that the water transmissivity is for a majority of conditions

much greater than the oil transmissivity and so, the total potentiometric surface remains almost constant during the test. Therefore, the changes in the elevation of the oil/air interface in the well represent changes in oil head (b.4).

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 is consistently met in all bail-down tests. More recently, Kirkman (2013) proposed a calculation methodology (Equation 2.58) 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.

$$T_o = \frac{r_{ce}^2 \ln(R_e/r_w)}{-2Jt} \ln \left(\frac{s_o(0)}{s_o(t)} \right) \quad (2.58)$$

where J is the J_{Ratio} defined by:

$$J = \frac{\Delta s_o}{\Delta b_o} \quad (2.59)$$

where: s_o Oil drawdown (m)
 b_o Oil thickness in the well (m)

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} (Figure 2.17).

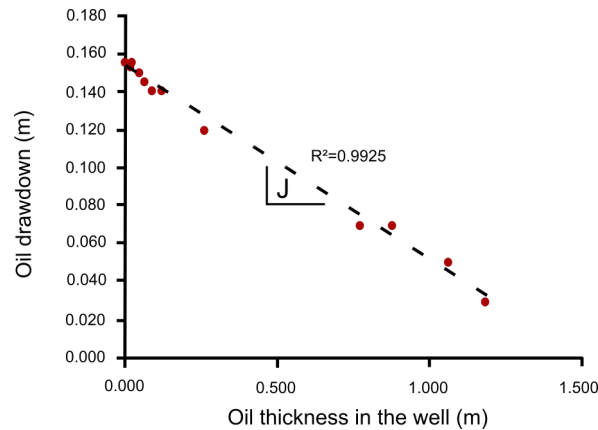


Figure 2.17: Example of gauged oil thickness versus oil drawdown for bail-down test

One can mention that when a set of data satisfies the Lundy and Zimmerman assumption for drawdown calculation, $J_{Ratio} = -1$. When a set of data satisfies the Huntley assumption for drawdown calculation, $J_{Ratio} = -(1 - \rho_{ro})$.

Approach Based on the Cooper Solution (Cooper *et al.*, 1967)

Cooper *et al.* (1967) proposed a solution for estimating the water transmissivity from a slug-test performed in a single-phase system. Their solution, based on the work made by Ferris and Knowles (1954), has been developed for a fully penetrating well in a confined aquifer.

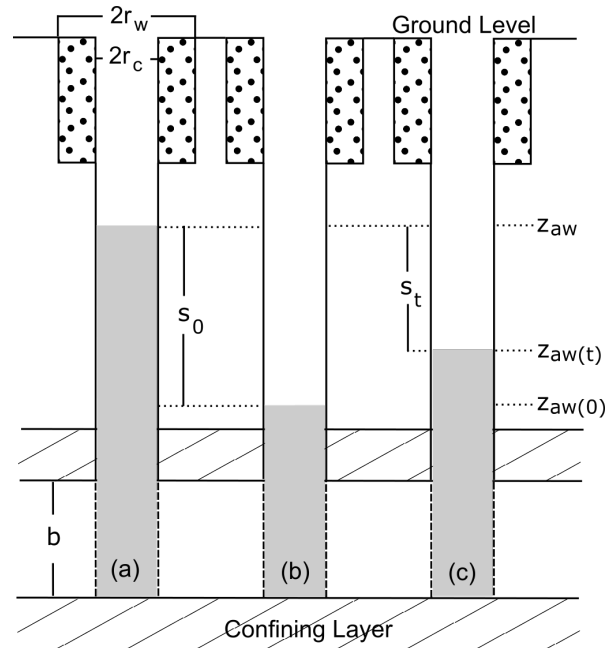


Figure 2.18: Geometry of fully penetrating wells in a confined aquifer a) before water bailing, b) at time t_0 and c) at time t after water bailing

Considering the symbols of Figure 2.18, the Cooper solution to calculate the water head change $H(t)$ inside the well at time t is solved with Bessel functions as follows:

$$H(t) = 8H_{(0)}\alpha/\pi^2 \int_0^\infty \frac{e^{-\beta u^2/\alpha} du}{u\Delta(u)} \quad (2.60)$$

where: $\alpha = r_c^2 S / r_w^2$ and $\beta = T_w t / r_w^2$

S	Aquifer storage coefficient	(-)
$H_{(0)}$	Initial water head change at time $t_{(0)}$ after the water is bailed out (m)	(-)
u	Integration Variable	(-)

The storage coefficient is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface (Todd, 1980). For a vertical column one meter by one meter extending through a confined aquifer, the storage coefficient S equals the volume of water (in cubic meter) released from the aquifer when the piezometric surface declines one meter. One can mention that the storage coefficient for an unconfined aquifer corresponds to its

specific yield.

From Equation 2.60, the water transmissivity is determined by plotting on a semi-logarithmic graph both theoretical and measured water head changes (or water drawdown $s(t)$) versus $\log(t)$ as shown Figure 2.19. The initial change in water head $H_{o(t)}$ is graphically estimated and, both water transmissivity and storage coefficient values are determined performing a visual curve matching.

In addition to the common assumptions already presented, the Cooper solution has been developed based on the following assumptions:

- (c.1) Confined aquifer with fully penetrating well.
- (c.2) Water flow to the well is unsteady.

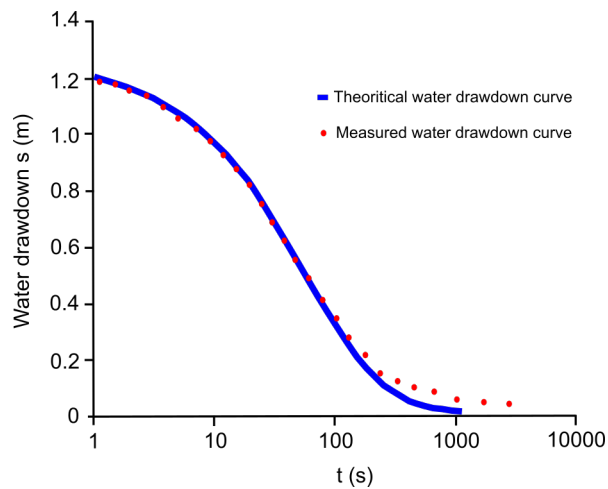


Figure 2.19: Example of bail-down test data analysis using Cooper equation

Beckett and Lyverse (2002) have suggested to directly apply the Cooper solution to estimate the oil transmissivity from a bail-down test performed in a two-phase system. When applied to oil in a well, the Cooper solution (Equation 2.60) is written in term of oil drawdown s_o , as follows:

$$\frac{s_o(t)}{s_o(0)} = 8\alpha/\pi^2 \int_0^\infty \frac{e^{-\beta u^2/\alpha} du}{u\Delta(u)} \quad (2.61)$$

where: $\beta = T_o t / r_w^2$

The oil transmissivity is determined following the same graphical approach as described for the water solution. The Cooper solution assumes that the drawdown change in the well is directly proportional to volume change in the groundwater system. This is not the case for an oil bail-down test and, therefore the resulting oil transmissivity values need to be multiplied by the oil density correction factor $(1/(1 - \rho_{ro}))$ (Beckett and Lyverse, 2002). For

oil in unconfined conditions, the storage coefficient corresponds to the oil specific yield, which is the oil that can be drained by the force of gravity. Therefore, its maximum estimated value should equal a reasonable drainable porosity value for the formation. An upper bound estimate would be 0.15 for coarse sands, 0.06 for fine sands and 0.004 to 0.025 for silts (Charbeneau, 2012).

Overall, oil transmissivity results are relatively insensitive to this parameter if realistic values are used (Charbeneau, 2012).

When applying the Cooper solution to a two-phase system, in addition to the common assumptions already presented, the following assumptions are made:

(d.1) Confined free oil layer with fully penetrating well.

(d.2) Oil flow to the well is unsteady.

Approach Based on the Jacob and Lohman Solution (Jacob and Lohman, 1952)

Considering a well fully penetrating an extensive confined aquifer, for constant drawdown (aquifer pumped at a constant rate) and variable discharge conditions in a single-phase system, Theis (1935) obtained the following solution:

$$s(t) = \frac{Q}{4\pi T_w} W(u) \quad (2.62)$$

where,

$$u = \frac{r_c^2 S}{4T_w t} \quad (2.63)$$

$W(u)$ is termed the well function and can be expanded as a convergent series as follows:

$$W(u) = \left[-0.5772 - \ln(u) + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} + \frac{u^4}{4.4!} + \dots \right] \quad (2.64)$$

Jacob and Lohman (1952) noted that, except for very early times, the relationship between decreasing discharge and time under constant drawdown condition, can be approximated by:

$$Q = \frac{4\pi T_w s(t)}{\ln(2.25T_w t / r_c^2 S)} \quad (2.65)$$

Equation 2.65 may be written:

$$\frac{1}{Q} = \frac{2.3}{4\pi T_w s(t)} \log \left(\frac{2.25T_w t}{r_c^2 S} \right) \quad (2.66)$$

Equation 2.66 implies that a plot of $1/Q$ versus $\log(t)$ should be linear, and the slope can be used to calculate the water transmissivity by:

$$T_w = \frac{2.3}{4\pi s(t) \Delta(1/Q)} \quad (2.67)$$

where: $\Delta(1/Q)$ is the change in $1/Q$ per log cycle

In addition to the common assumptions already presented, the Jacob and Lohman (1952) solution is based on the following assumptions:

- (e.1) Confined aquifer with fully penetrating well.
- (e.2) The well is pumped at a constant discharge rate.

During the recovery from a bail-down test, the well is not really being pumped but is recovering from a rapid removal of fluid from the well. Therefore, to apply the Jacob and Lohman solution for bail-down test interpretation in two-phase condition, Huntley (2000) suggested that the discharge (Q) must be calculated from the change in volume of oil in the well. That is,

$$Q = \frac{\pi r_{ce}^2 (\Delta z_{ow} - \Delta z_{oa})}{\Delta(t)} \quad (2.68)$$

This method assumes that the oil drawdown s_o is constant during the recovery period and is known. In the case of this critical assumption is not met or measurement errors, unknown error may be introduced in the oil transmissivity calculation. When drawdown is varying substantially, Huntley (2000) proposed to further modify the Equation 2.66, as follows:

$$\frac{s(t)}{Q} = \frac{2.3}{4\pi T_o} \log \left(\frac{2.25 T_o t}{r_{ce}^2 S} \right) \quad (2.69)$$

allowing to plot (s/Q) versus t . The oil transmissivity is then calculated by:

$$T_o = \frac{2.3}{4\pi s(t) \Delta(s/Q)} \quad (2.70)$$

where: $\Delta(s/Q)$ is the change in s/Q per log cycle

Huntley noticed that when using this solution for an oil bail-down test, an additional scatter is introduced in the data. This scatter is produced by the fact that the thickness of oil in the well is changing slowly, and small errors in measurement can markedly affect the answer, and particularly if measurements are taken close together (Huntley, 2000).

To minimize this scatter effect, Huntley suggested to look at the cumulative change in oil volume in the well at any time. Equation (2.69) becomes:

$$(s\Delta t) = \frac{2.3(Q\Delta t)}{4\pi T_o} \log \left(\frac{2.25 T_o t}{r_{ce}^2 S} \right) \quad (2.71)$$

where: $(Q\Delta t)$ is the change in oil volume in the well over the time step interval

Summing both sides of Equation (2.71) gives:

$$\sum_{i=1}^n (s_i \Delta t_i) = \frac{2.3}{4\pi T_o} \sum_{i=1}^n \left[Q_i \Delta t_i \log \left(\frac{2.25 T_o t}{r_{ce}^2 S} \right) \right] \quad (2.72)$$

The approach to solve Equation (2.72) is to calculate both right and left hand sides using assumed values of two unknowns: T and $r^2 S$. The squared residual is calculated for each step. Values of T and $r^2 S$ are then iteratively adjusted to minimize the sum of squared residual. A visual confirmation of a solution can be produced by plotting the left-hand side of Equation (2.72) versus the right-hand side as shown Figure 2.20.

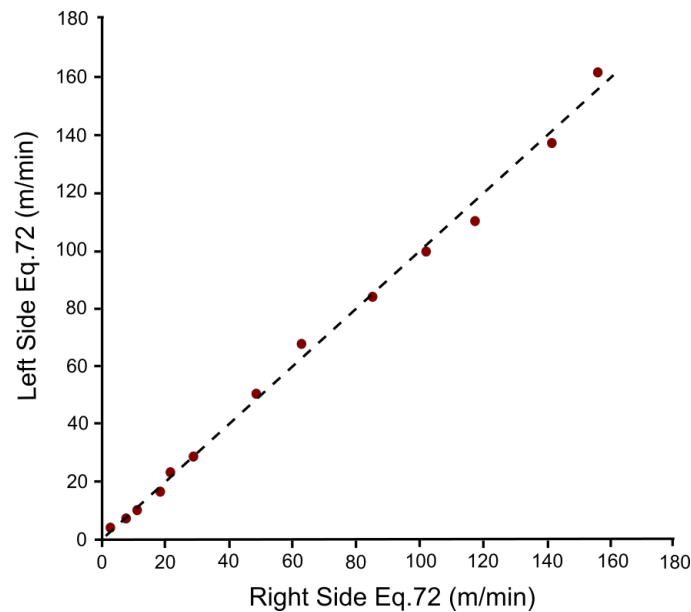


Figure 2.20: Example of bail-down test data analysis using Jacob and Lohman modified solution (Huntley, 2000). Points are measured data from a field test, using calculated transmissivity

In addition to the common assumptions already presented, the modified Jacob and Lohman for bail-down test in a two-phase system, given by Equation (2.72) is based on the following assumptions:

- (f.1) Confined free oil layer with fully penetrating well.
- (f.2) Oil recovery is assumed to be slow enough to consider a pseudo-steady-state condition.

Contrary to a solution based on the Bouwer and Rice method which is independent of the absolute time, for the solutions using Cooper, and Jacob and Lohman, absolute time is critical. Absolute time is critical because both solutions include an oil storage coefficient as a parameter, which represents a capacitance factor (Charbeneau, 2012). Therefore, the effective time origin needs to be adjusted (time adjustment) when early time data are eliminated

(cut-off time) because of filter pack drainage. Literature suggests that the time adjustment ($Time_{adj}$) and the time cut-off ($Time_{cut}$) may be related through the following (Charbeneau, 2012):

$$Time_{adj} = 0.6 \cdot Time_{cut} \quad (2.73)$$

This review of the theoretical fundamentals of the three commonly used methods of bail-down test interpretation for the oil/water system [modified Jacob and Lohman (Huntley, 2000), modified Bouwer and Rice (Huntley, 2000; Lundy and Zimmerman, 1996), and modified Cooper *et al.* (Beckett and Lyverse, 2002) solutions] shows that these standard approaches are all based on different assumptions and boundary conditions. These key differences are summarized in the Table 2.2.

Table 2.2: Key assumption and boundary conditions of oil bail-down interpretation methods

Authors	Key Assumptions and Boundary Conditions
Bouwer and Rice modified solutions Lundy and Zimmerman (1996) and Huntley (2000)	<ul style="list-style-type: none"> - Return flow to the well is steady state. (b.1) - Oil drawdown initiated by the oil removal around the well is negligible when compared with the oil layer thickness. (b.2) - For Lundy and Zimmerman (1996) solution: Changes in oil thickness are assumed to represent changes in oil head. (b.3) - For Huntley (2000) solution: Changes in the elevation of the oil/air interface in the well represent changes in oil head. (b.4)
Cooper <i>et al.</i> modified solution Beckett and Lyverse (2002)	<ul style="list-style-type: none"> - Confined aquifer with fully penetrating well. (d.1) - Oil flow to the well is unsteady. (d.2)
Jacob and Lohman modified solution Huntley (2000)	<ul style="list-style-type: none"> - Confined aquifer with fully penetrating well. (f.1) - Oil recovery is assumed to be slow enough to consider a pseudo steady state condition. (f.2)

Chapter 3

Validity of Bail-Down Tests to Estimate the Oil Transmissivity

The review of the theoretical fundamentals of the three commonly used methods of bail-down tests interpretation for a two-phase system modified Jacob and Lohman (Huntley, 2000), modified Bouwer and Rice (Lundy and Zimmerman, 1996; Huntley, 2000), and modified Cooper *et al.* (Beckett and Lyverse, 2002) shows that these standard approaches are all based on different assumptions and boundary conditions. These different boundary condition constraints are often not met during a bail-down test. For example, a boundary requirement for the modified Bouwer and Rice method (Huntley, 2000) is that the return flow to a well be steady-state. This condition is not met during a bail-down test when recording the transient response of the air/oil and oil/water interfaces after instantaneous removal of the oil phase. In addition, Lundy and Zimmerman (1996) and Huntley (2000) introduced in their modified Bouwer and Rice solutions different important simplifying assumptions to allow calculation of the drawdowns. Therefore, the error introduced by these interpretations of the bail-down tests is still under discussion (Batu, 2012, 2013; Charbeneau *et al.*, 2013).

Previous studies have shown that the oil transmissivity value can be estimated with a coefficient of variation (ratio of the standard deviation to mean value) of twenty percent or less when considering analyses using the three common methods mentioned above (Charbeneau, 2012). However, very few studies have assessed the validity of the oil transmissivity values estimated using these interpretation methods. Huntley *et al.* (1992) and Kolhatkar *et al.* (2000) showed that the estimated oil transmissivity using the Jacob and Lohman (1952), and modified Bouwer and Rice (Lundy and Zimmerman, 1996; Huntley, 2000) methods fairly agreed (20 to 30% ratio) with the predicted oil transmissivity calculated using the theoretical model proposed by Parker *et al.* (1987). However, Huntley *et al.* (1992) and Kolhatkar *et al.* (2000) made studies in non-homogeneous conditions and further discussion regarding the uncertainty introduced by estimating the Van Genuchten parameters n and α (Van Genuchten, 1980), to predict the oil transmissivity with the theoretical approach, is

needed. Others compared the results from different analytical solutions working with data from only two to three wells (Krol, 1995; Huntley, 2000; Charbeneau, 2012), and Krol (1995) in particular found transmissivity values with an order of magnitude difference between those obtained from the modified Bouwer and Rice (Lundy and Zimmerman, 1996) and those obtained from the modified Jacob and Lohman (1952) methods. Overall, the validity of the oil transmissivity values obtained from the three commonly used methods of interpretation is not clearly confirmed and the approaches have not been peer-reviewed. Therefore, in order to assess the validity of the bail-down test interpretation for two-phase systems, two different studies were performed; one at laboratory scale and the second at field scale.

The first study was based on bail-down test simulations at laboratory scale with known conditions, in order to make a robust validation of the bail-down test interpretation for two-phase systems. The objectives were to i) compare the oil transmissivity values estimated from bail-down test interpretation with those predicted from a theoretical model (Parker *et al.*, 1987) using measured key parameters (hydraulic conductivity, Van Genuchten parameters, oil properties), ii) confirm the consistency of the oil transmissivity values estimated with two commonly used interpretation methods: the modified Bouwer and Rice (Huntley, 2000) and the modified Cooper methods (Beckett and Lyverse, 2002), and iii) compare the variation in transmissivity values between the oil imbibition and the drainage phases. The bail-down tests were completed on a laboratory-scale radial model filled with homogeneous soil, observing several oil thicknesses measured after imbibition and drainage steps. In parallel with the bail-down tests, the homogeneous conditions of the laboratory model allowed the oil transmissivity using the Parker theoretical model (Parker *et al.*, 1987) to be calculated from the oil thickness measured in the wells.

The outcomes of this study are presented in the first part of this Chapter which is organized as follows. Section 3.1.1 presents the laboratory simulations through i) the conceptual design of the experiment, ii) the physical parameters describing the porous media and oil, and finally iii) the description of the simulation process and sequences. Section 3.1.2 presents the results comparing the measured oil saturation and transmissivity with those predicted for equilibrium conditions using Parker's theoretical model. This section includes a discussion of the key findings. Finally, Section 3.1.3 summarises the key outcomes of this study and enlarges on some of the conclusions.

A second study has been conducted at field scale with unknown, heterogeneous soil conditions. The objectives were to i) assess, using a data set of 289 bail-down tests, the validity of the oil transmissivity values obtained from the three commonly-used methods of interpretation the modified Bouwer and Rice (Lundy and Zimmerman, 1996; Huntley, 2000), the modified Cooper methods (Beckett and Lyverse, 2002), and the modified Jacob and Lohman (Huntley, 2000) solutions, ii) verify if the simplifying assumptions proposed by Lundy and Zimmerman (1996) and Huntley (2000) to calculate the drawdown are consistently met for the site-specific conditions and oil characteristics, and iii) assess the relationship between temporal changes in oil thickness and transmissivity during long-term oil extraction.

The outcomes of this study are presented in the second part of this Chapter which is organized as follows. Section 3.2.1 presents the field case study including i) the site-specific

conditions, the oil physical properties and the oil collection system, and ii) a description of the bail-down test protocol. In Section 3.2.2, 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 3.2.3 expands the conclusions from Section 3.2.2 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.

3.1 Oil Transmissivity Estimation Using Bail-down Test in Homogeneous Conditions at Laboratory Scale

A paper related to this section has been submitted and is under review by Transport in Porous Media journal.

3.1.1 Material and Methods

A radial model was built to perform laboratory scale simulations of bail-down tests in homogenous conditions. The tests were performed for several oil thicknesses during the oil imbibition and the drainage of the model. From these datasets the oil permeability was estimated using the modified Bouwer and Rice (Huntley, 2000) and Cooper solutions (Beckett and Lyverse, 2002).

The laboratory model was constructed of clear glass to represent a radial portion of a domain around a well. Its dimensions allow for a significant thickness of the oil phases to collect in the wells while the water level is maintained constant, representing groundwater beneath the oil for the sake of realism (Figure 3.1).

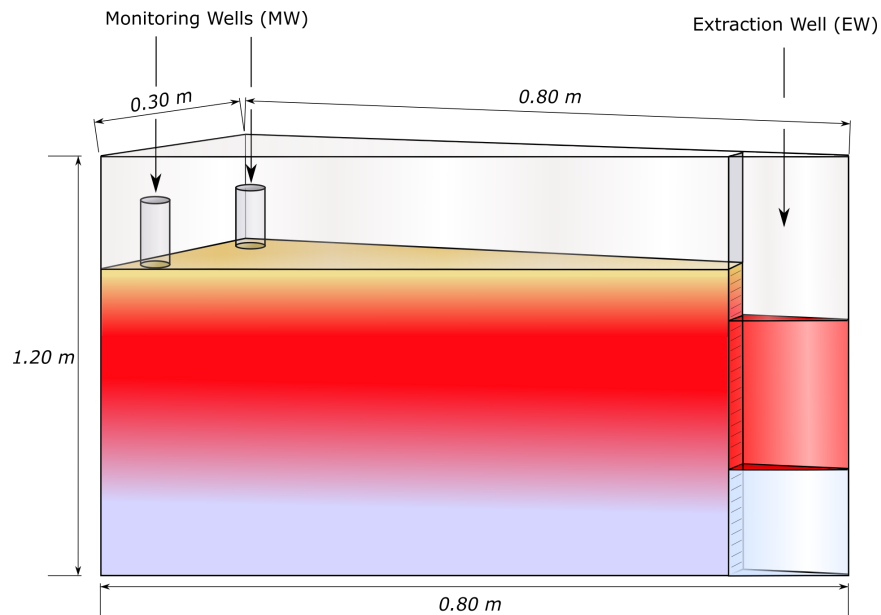


Figure 3.1: Pilot conceptual model

The two monitoring wells (casing diameter: 0.05 m) were completely screened from the top to bottom of the domain. These wells were used i) to verify the equilibrium conditions before starting the tests and, ii) for re-injection purposes. The extraction well was screened from the bottom to the top of the domain, the radius of the casing was 0.125 m and the screened width in contact with the porous media was 0.045 m. The bail-down tests were performed from the extraction well.

In order to realize the laboratory measurements in homogenous conditions, the scaled model

was filled with coarse sand with a grain size distribution ranging from 0.4 to 0.9 mm. The wells were implemented without gravel pack, but with a filter cloth between the casing and the porous media to avoid clogging of the screened section. No clogging of the filter cloth has been visually observed during the tests. Table 3.1 presents the physical properties of the soil and oil. All these parameters were measured, apart from the Van Genuchten parameters α and n , which were estimated by fitting the curve of the Van Genuchten equation to the plot of the measured water saturation at different levels above the air/water interface. The oil viscosity was measured with a rotational viscometer, and the interfacial tensions were measured using the pendant drop method.

Table 3.1: Physical properties of the soil and oil

Van Genuchten Parameter α	22 m ⁻¹
Van Genuchten Parameter n	4.5
Soil Porosity η	0.35
Oil Relative Density ρ_o	0.917
Oil Dynamic Viscosity μ_o (20°C)	72 cP
Interfacial Tension Oil/Air σ_{oa}	32.6 dynes.cm ⁻¹
Interfacial Tension Oil/Water σ_{ow}	24.8 dynes.cm ⁻¹
Interfacial Tension Air/Water σ_{aw} (water 24 h in contact with the oil to allow equilibrium)	71.9 dynes.cm ⁻¹

The scaled model was filled according to the following sequence and each phase allowed experiments to be completed as described.

- (A) 20 cm of dry sand.
- (B) Full saturation of the sand with water.
Porosity measurement and hydraulic conductivity calculation under steady conditions using the Darcy equation.
- (C) Drainage of water down to 10 cm of water in the monitoring wells.
Residual water saturation measurement.
- (D) Full saturation with oil by filling from the top sand surface. Adding oil stopped when it started pooling at the sand surface.
- (E) Addition of 10 cm of sand at 10% water saturation.
Hydraulic oil conductivity calculation under transient conditions using the Huntley (Equation 2.57) method and the Beckett and Lyverse (Equation 2.60) method for bail-down testing.
This allowed measurement of the volume of oil in the system.

Steps (A), (D) and (E) were then repeated to complete the filling of the scale model, as shown in Figure 3.2. At filling steps 7, 9 and 11, after the interface levels were equal and stable in all the wells, all the measurements of the phase (E) were performed, allowing the determination of the hydraulic oil conductivity for different oil thicknesses.

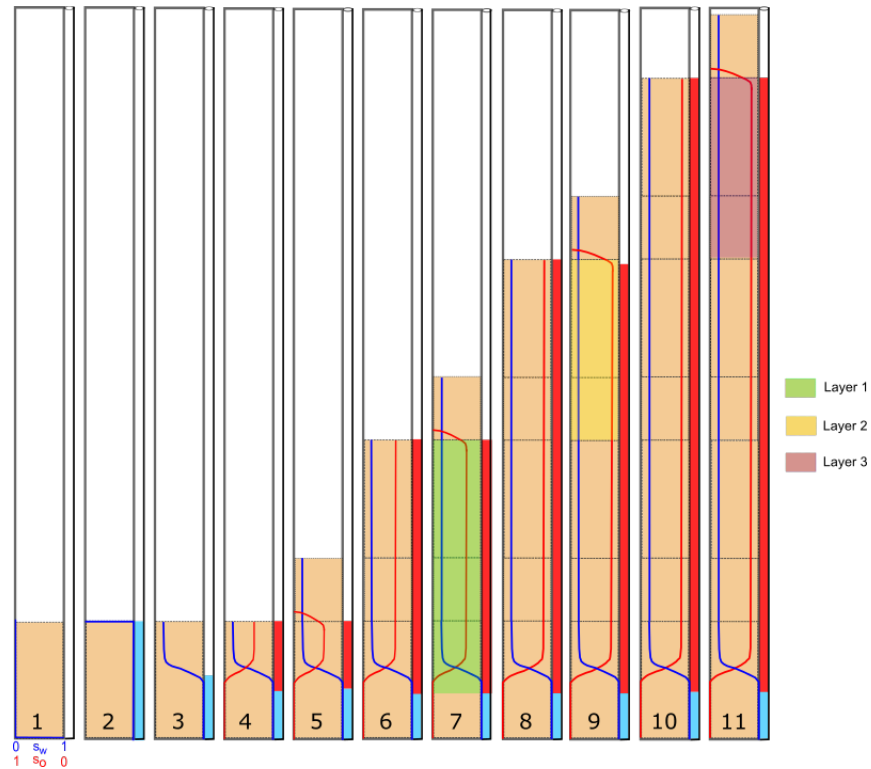


Figure 3.2: Schematic view of the pilot filling process including the oil (red) and water (blue) saturation curves

After completion of the oil imbibition, oil drainage was performed by decreasing the oil level by 30 cm each time, reaching the oil thicknesses of steps 9, and then 7. The measurements of the phase (E) were performed for each step after the interface levels were equal and stable in all the wells.

Through the phases (A) to (E), the fluid and soil volumes were calculated from the measured mass added, allowing saturation calculations using the laboratory model dimensions presented in Figure 3.3.

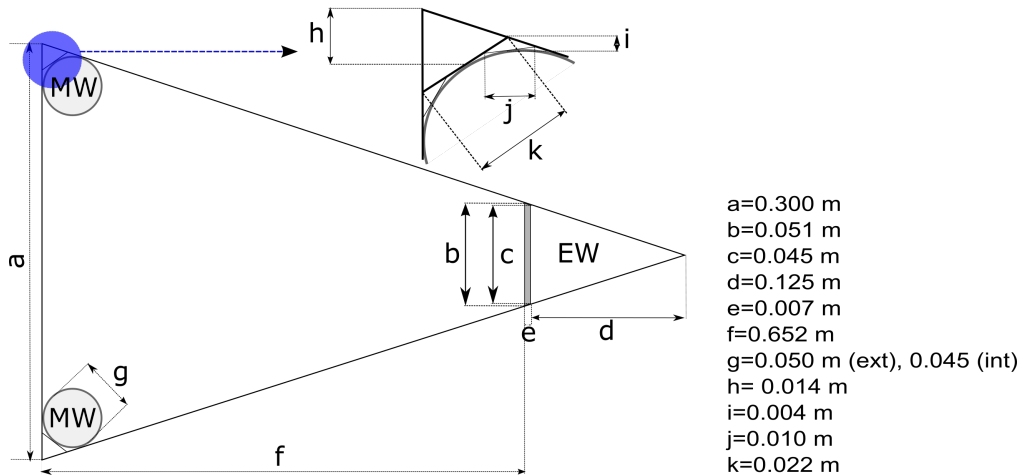


Figure 3.3: Plan view and pilot dimensions

3.1.2 Results

Oil Saturation

The average oil saturation calculated from the measured oil volumes in the laboratory scale pilot varied from 0.70 to 0.90 and the residual water saturation in the vadose zone was close to 0.10 for this type of sand. These oil saturations were measured using the volume of oil introduced in the pilot at the filling steps 7, 9 and 11, and represent an average saturation of oil over each sand layer (Figure 3.2). It is assumed that the volume of oil present in the oil/air capillary fringe located in the upper 10 cm of sand is negligible. This assumption is supported by the fact that the oil thickness in the well between steps 6 and 7, 8 and 9, and 10 and 11 did not change.

- At filling step 7, the oil thickness measured in the extraction wells was 0.33 m and the measured average oil saturation was 0.70 in sand layer 1.
- At filling step 9, the oil thickness measured in the extraction wells was 0.57 m and the measured average oil saturation was 0.88 in sand layer 2.
- At filling step 11, the oil thickness measured in the extraction wells was 0.84 m and the measured average oil saturation was 0.90 in sand layer 3.

For each of these three steps, the oil thicknesses measured in the three wells were the same, suggesting that a continuum homogeneous body of oil existed in the porous media. This condition was not met at step 4, where the oil thickness measured in the extraction wells was 0.050 m, 0.040 m in one of the monitoring wells and 0.065 m in the other one. These differences in the oil thickness were probably the result of a heterogeneous distribution of the oil across the soil, not forming a continuous mobile oil layer.

Assuming the equilibrium condition at steps 7, 9 and 11, one can use the measured oil thickness to calculate the theoretical oil vertical distribution curve under equilibrium conditions,

applying Equations (2.30), (2.31) and (2.36), and the Van Genuchten parameters measured with the water saturation in an air/water system. The oil saturation was calculated for each centimetric layer of sand. By using these calculated oil saturations, the average oil saturations in Layers 1, 2 and 3 were calculated for filling steps 7, 9 and 11 (Table 3.2).

Table 3.2: Measured and calculated average oil saturations in the pilot

	Measured oil thickness (m)	Measured average oil saturation	Theoretical average oil saturation
Filling Step 7	0.33	0.70	0.33
Filling Step 9	0.57	0.88	0.85
Filling Step 11	0.84	0.90	0.89

Comparing the measured and calculated average oil saturations, it appears that for Layer 1 (0.33 m of oil in the wells) the calculated average oil saturation is significantly lower than the values measured in the pilot, while for the two other layers the average calculated and measured oil saturations are very similar. This difference for the first layer suggests that the pilot didn't reach the vertical equilibrium condition at the time of the measurements, one week after the oil had been introduced in the porous media, although no oil movement could be measured. In order to represent the true saturation of oil in the model, the oil vertical distribution curve has been fitted to reach the same average oil saturation as the measured one. Both oil vertical distribution curves are shown in Figure 3.4.

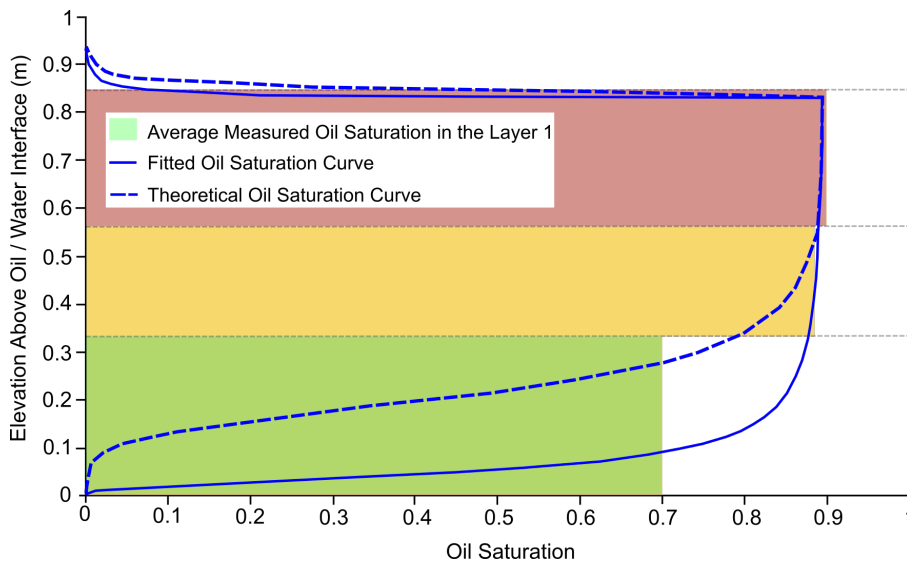


Figure 3.4: Theoretical and fitted oil saturation at equilibrium conditions and measured oil saturation in the pilot

Water and Oil Hydraulic Conductivity

The hydraulic conductivity of the porous medium is $2.0 \times 10^{-3} \text{ m.s}^{-1}$. This hydraulic conductivity was obtained under steady state conditions by pumping the water from the extraction wells (EW) and re-injecting the water into one of the two monitoring wells (MW). When the equilibrium conditions were reached, the water levels in both monitoring wells were the same and the gradient between the monitoring wells and the extraction well was constant. The geometry of the laboratory model and the experiment protocol did not allow an analytical approach, thus a numerical model was applied to estimate the water permeability value (Figure 3.5). A finite volume model (FiPy, Guyer *et al.* (2009)) was used to correctly take into account the geometry of the system.

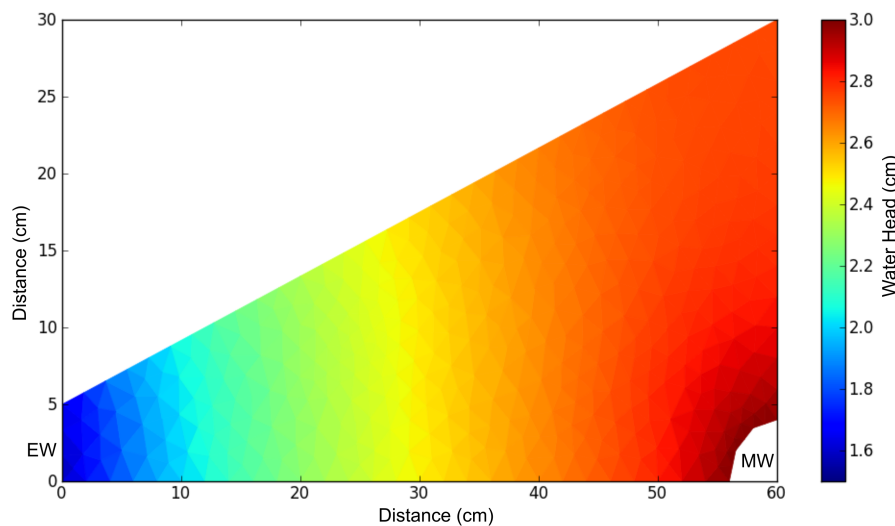


Figure 3.5: Numerical model outcome for $K_w=2 \times 10^{-3} \text{ m.s}^{-1}$

Before interpreting the bail-down datasets with both approaches Huntley (2000) and Beckett and Lyverse (2002), the oil drawdown/discharge relation was plotted. For all the bail-down datasets, these relations showed that the linear part of the curve did not approach zero drawdown at zero discharge. Such behavior suggests that the porous media and the oil of the extraction wells were not initially in complete equilibrium (Charbeneau, 2012). Figure 3.6 shows two examples using bail-down datasets from Steps 7 and 9 during the imbibition phase. In curve (a) the extrapolated limit has zero discharge with $s_o=0.042 \text{ m}$, and in curve (b) the extrapolated limit has zero discharge with $s_o=0.046 \text{ m}$.

Drawdown corrections of $\Delta s_o=0.042 \text{ m}$ and $\Delta s_o=0.046 \text{ m}$ were applied to the data before the oil transmissivity interpretation. Corrections were also required for the other datasets as follows: Step 11 $\Delta s_o=0.08 \text{ m}$, Step 7 during the drainage phase $\Delta s_o=0.026 \text{ m}$, and Step 9 during the drainage phase $\Delta s_o=0.031 \text{ m}$.

For the modified Bouwer and Rice method (Huntley, 2000), the total potentiometric surface was calculated and plotted versus elapsed time (Figure 3.7(a)). As expected for homogeneous

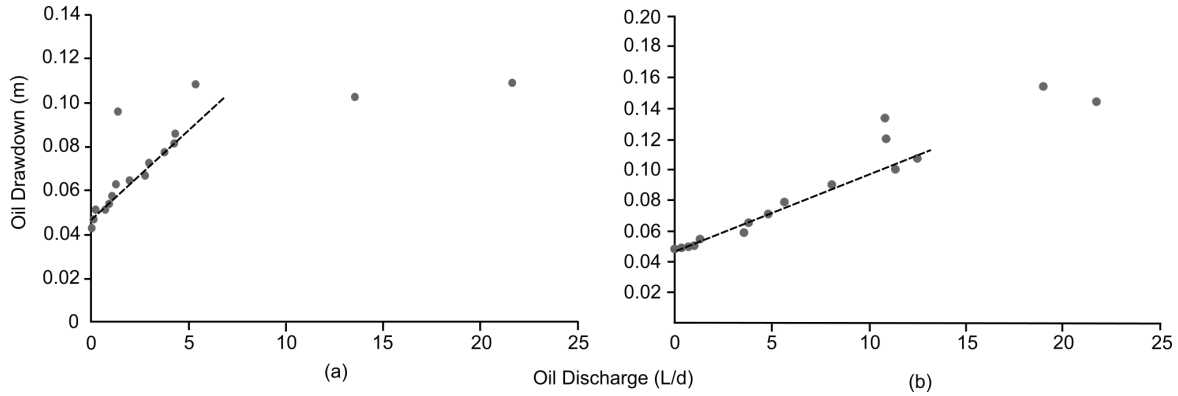


Figure 3.6: Oil drawdown/discharge relation – bail-down at step 7 (a) and 9 (b)

and highly permeable conditions, these curves confirmed that the total potentiometric surface was constant for all the bail-down tests, allowing the modified Bouwer and Rice method (Huntley, 2000) to be applied. For the modified Cooper method, the calculated drawdowns versus elapsed time curves have been fitted to the measured drawdown iteratively by minimizing the sum of the squared residuals (Figure 3.7(b)). The storage coefficient was set to 0.08 as suggested by the literature for this type of soil.

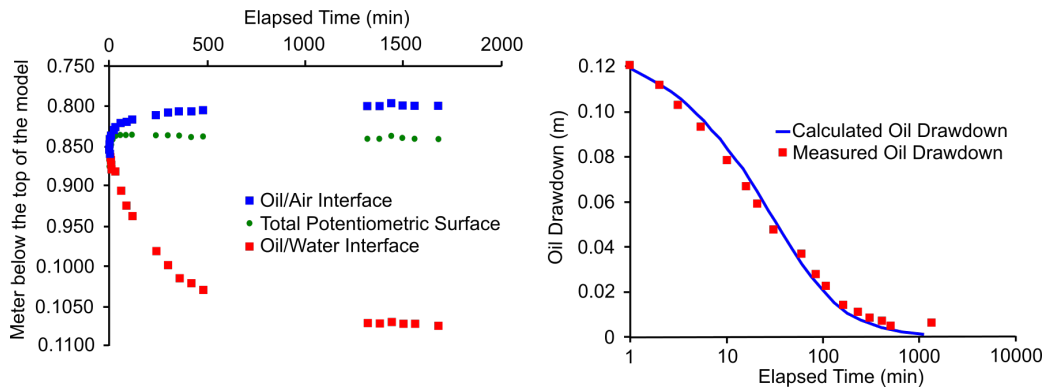


Figure 3.7: (a) Fluid elevation changes after oil removal and (b) calculated and measured oil drawdown curve using the modified Cooper method (Beckett and Lyverse, 2002)

In parallel, the theoretical relative oil permeabilities were calculated for the same model filling steps using the Parker method (Parker *et al.*, 1987) combining the Van Genuchten parametric model with the Burdine relative oil permeability model (Equation 2.43). This analytical model for calculating kr_o was applied for each centimetric soil layer by using the oil saturations corresponding to the fitted oil vertical distribution curve, and the measured water permeability. Considering the thickness of the soil layer, the average k_{ro} was calculated

using:

$$\overline{k_{ro}}(S_w, S_o) = \frac{\sum_{i=1}^n k_{ro} b_i}{b_{total}} \quad (3.1)$$

where: $\overline{k_{ro}}$ Average hydraulic oil conductivity (-)

The hydraulic oil conductivity K_o was determined inserting the average k_{ro} value in Equation (2.46). The hydraulic oil conductivity multiplied by the oil thickness in the wells gave the oil transmissivity, denoted TB/VG in Table 3.3. These theoretical oil transmissivity values were compared to the values obtained from the bail-down test interpretation, denoted TB&R (modified Bouwer and Rice method) and TCoop (modified Cooper method).

Table 3.3: Calculated and estimated oil transmissivities in m²/s

Oil Thickness (m)	TB&R Imbibition	TB&R Drainage	TCoop Imbibition	TCoop Drainage	TB/VG
0.33 (filling step 7)	3.1×10^{-6}	3.5×10^{-6}	3.7×10^{-6}	4.5×10^{-6}	4.0×10^{-6}
0.57 (filling step 9)	8.5×10^{-6}	1.0×10^{-5}	7.3×10^{-6}	6.7×10^{-6}	8.4×10^{-6}
0.84 (filling step 11)	1.4×10^{-5}		1.1×10^{-5}		1.3×10^{-5}

The results show limited differences in the oil transmissivity values estimated from the imbibition and drainage phases. Considering each method of interpretation, the difference between the oil transmissivity estimated for the imbibition and the drainage phases ranges from 9 to 23%. These differences can be explained by i) the uncertainties in the measurements and the bail-down test interpretations, and ii) by the hysteresis phenomena, which is the non-unique relationship between capillary pressure and saturation.

Both interpretation methods for bail-down tests give similar oil transmissivity values. The difference for the same oil thickness is between 14 and 22% during the imbibition phase and reaches a maximum of 36% during the drainage. This magnitude of difference is consistent with what is reported in the literature (Charbeneau, 2012). Again, the uncertainties mentioned above also play a role here. Finally, the oil transmissivity values estimated with both methods of interpretation agree well with the predicted oil transmissivity from Parker theoretical model. Assuming that the Parker analytical model for calculating k_{ro} gives representative values of the real hydraulic oil conductivity of a porous media, one can conclude that this result confirms the validity of the bail-down test for interpreting the oil transmissivity of an oil phase in homogeneous conditions. Figure 3.8 summarizes the results considering the imbibition phase for the bail-down test interpretation results and including the oil transmissivity calculated using the Parker *et al.* (1987) method with the fitted values of the Van Genuchten parameters α and n .

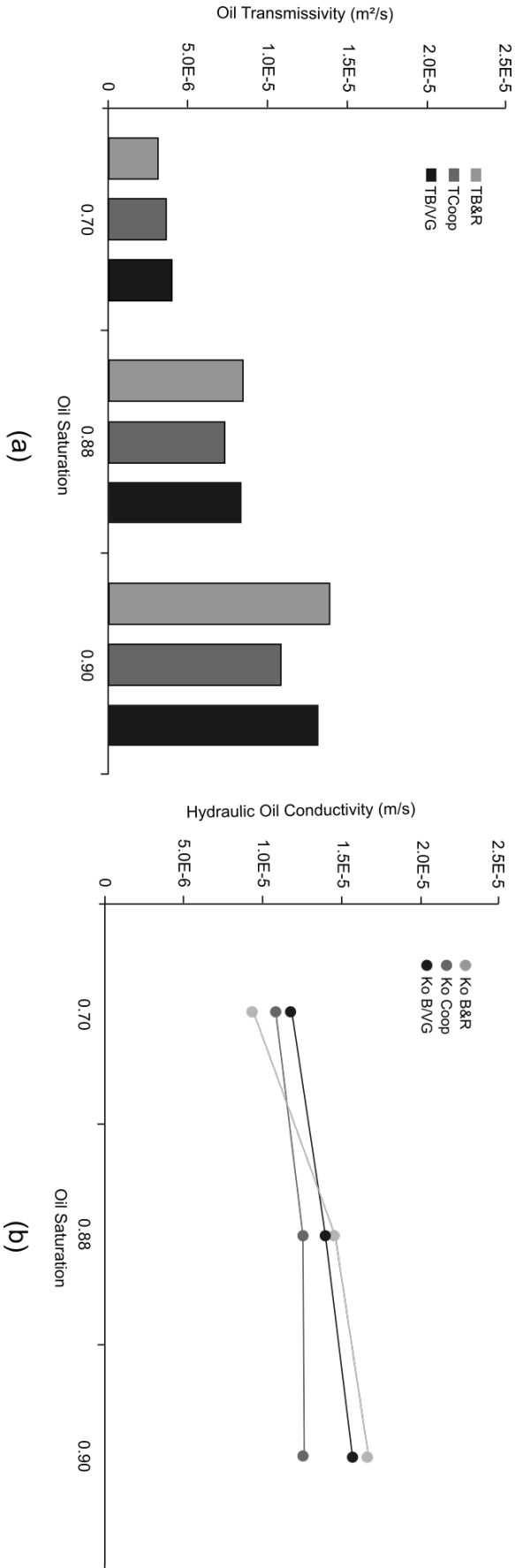


Figure 3.8: (a) Oil transmissivity and (b) hydraulic oil conductivity values versus oil saturation estimated using the modified Bouwer and Rice (Huntley, 2000), the modified Cooper *et al.* (Beckett and Lyverse, 2002) bail-down test interpretation methods, and Parker *et al.* (1987) analytical model

The Burdine model for k_{ro} has been applied, as the literature does suggest that this model may be more appropriate for coarse-grained soils (Charbeneau, 2007), which is the case of the sand used for the laboratory scale pilot, while the Mualem model must be used for fine-grained materials. However, the Mualem model has been used as well in order to assess the oil transmissivity difference with the values obtained using Burdine model and with the bail-down test interpretation. As usually encountered, the Mualem model predicts larger values for the oil relative permeability than the Burdine model (between 30 to 40% higher). The Van Genuchten parametric model has been used consistently, keeping in mind that for this range of saturation, the Brooks and Corey model should give similar results. These results confirm the validity of the oil transmissivity values estimated by the modified Bouwer and Rice (Huntley, 2000) and the modified Cooper (Beckett and Lyverse, 2002) methods whereas the conditions of the test do not meet all the assumptions and boundary conditions of each analytical solution.

The modified Bouwer and Rice method (Huntley, 2000) is based on a steady-state confined radial flow model and the major boundary requirements are: (a) aquifer/LNAPL zone has infinite area extent; (b) aquifer and LNAPL zone is homogeneous and of uniform thickness; (c) aquifer/LNAPL total potentiometric surface is initially horizontal; (d) the oil volume recovered to initiate the test is instantaneous and (e) return flow is steady-state (Beckett and Huntley, 2015b); (f) the initial drawdown is relatively small compared to the total aquifer thickness. The modified Cooper method (Beckett and Lyverse, 2002) is based on a transient confined radial flow model and the main boundary requirements are: (g) the well fully penetrates the confined aquifer; (h) the oil volume recovered to initiate the test is instantaneous and (i) return flow is transient. Considering the conditions of the laboratory scale simulation, a first analysis suggests that conditions (a), (e) and (f) of the modified Bouwer and Rice and condition (g) of the modified Cooper method are not met during the bail-down test. It is thus interesting to understand why the estimated transmissivities are correct although some assumptions are not verified.

The high oil viscosity (around 80 cP) significantly slows down the flow of oil. Therefore, the important initial drawdown triggered by the oil recovery leads, in fact, to a limited drawdown in the adjacent formation, and so the radius of influence of the test is limited to the portion of the oil phase closer to the well. Based on this assumption, one can consider that the boundary requirements (a), (f) and (g), when applied to the formation, are verified during the test. Assumption (e) is not met in any bail-down test. However, with oil, the flow rate is much lower than with water and therefore the return flow to the well is slow and can be more easily considered as a series of steady flow states.

Therefore, the oil viscosity is likely to be the key parameter which makes the bail-down test interpretation for an oil/water system valid allowing critical assumptions and boundary conditions of the analytical solutions to be verified. It is important to mention that the above conclusions are valid for the conditions of the test, and especially for homogeneous conditions, viscous oil and oil saturation greater than 0.7. For less viscous oil, it seems likely that more vertical oil movement occurs which may introduce substantial error when interpreting the bail-down tests. In addition, it is clear that below a certain oil saturation, important

boundary conditions are not verified, as the oil may not form a homogeneous continuum in the formation. This assumption is supported by the observation of filling step 5, which makes obvious that the oil does not form a homogeneous continuum. At this step, the measured oil saturation is 34%. For each specific condition, there is a minimum oil saturation which needs to be reached to make the bail-down interpretation valid. The critical oil saturation is specific to each test condition and closely related to the intrinsic permeability of the porous media, to the grain-size distribution which directly influences the capillary curve, and finally the oil viscosity.

3.1.3 Conclusions

The laboratory scale simulation has confirmed the validity of the modified Bouwer and Rice (Huntley, 2000) and modified Cooper (Beckett and Lyverse, 2002) methods for estimating the oil transmissivity from bail-down test datasets. To our knowledge, this is the first laboratory validation of bail-down tests in two-phase system. The key outcomes of this study are:

- The estimated oil transmissivity from bail-down test interpretation agrees with the predicted oil transmissivity using the Parker *et al.* (1987) theoretical model in homogeneous conditions.
- It has been shown that the bail-down test interpretation for an oil/water system gives correct transmissivities because the properties of oil lead to a situation where the major boundary condition constraints are almost validated.
- These results suggest that during the bail-down, the oil is flowing mainly horizontally and that the oil thickness stays almost constant in the adjacent formation.
- A constant oil thickness in the adjacent formation during extraction is a condition describing flow to a well in a confined aquifer. This justifies the validity of the results obtained using the modified Cooper method.
- Due to all these properties, the unconfined or confined solutions for bail-down test interpretation can be used interchangeably for an oil/water system.
- The difference in the oil transmissivity values estimated by both methods of interpretation is around 20%, which is consistent with the conclusions of previous studies (Charbeneau, 2012; Palmier *et al.*, 2016).
- There are differences of a magnitude of 20% between the oil transmissivity estimated during the imbibition and drainage phases, which may reflect the hysteresis phenomena or measurement errors.

The modified Bouwer and Rice (Huntley, 2000) and the modified Cooper (Beckett and Lyverse, 2002) methods for bail-down test interpretation were validated for viscous oil in a homogeneous and quite permeable medium. These methods worked very well for the conditions tested, and their applicability to other untested conditions (less viscous products,

heterogeneous medium) needs to be confirmed. This study also showed that below a certain oil concentration, the medium was not equilibrated and the results of the bail down did not clearly agree with the theory. This observation may have consequences for the characterisation of thin oil layers.

3.2 Oil Transmissivity Estimation Using Bail-down Test in Heterogeneous Conditions at Field Scale

A paper related to this section has been published in Groundwater Monitoring and Remediation journal (Annex B).

The laboratory scale study confirms the validity of bail-down tests for estimating the oil transmissivity for unconfined oil layer in homogeneous conditions. However, most of the sites present heterogeneous conditions and oil can be present in unconfined, confined or perched conditions. Therefore, it is important to assess the validity of the commonly used bail-down test methods in field conditions.

3.2.1 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 3.9).

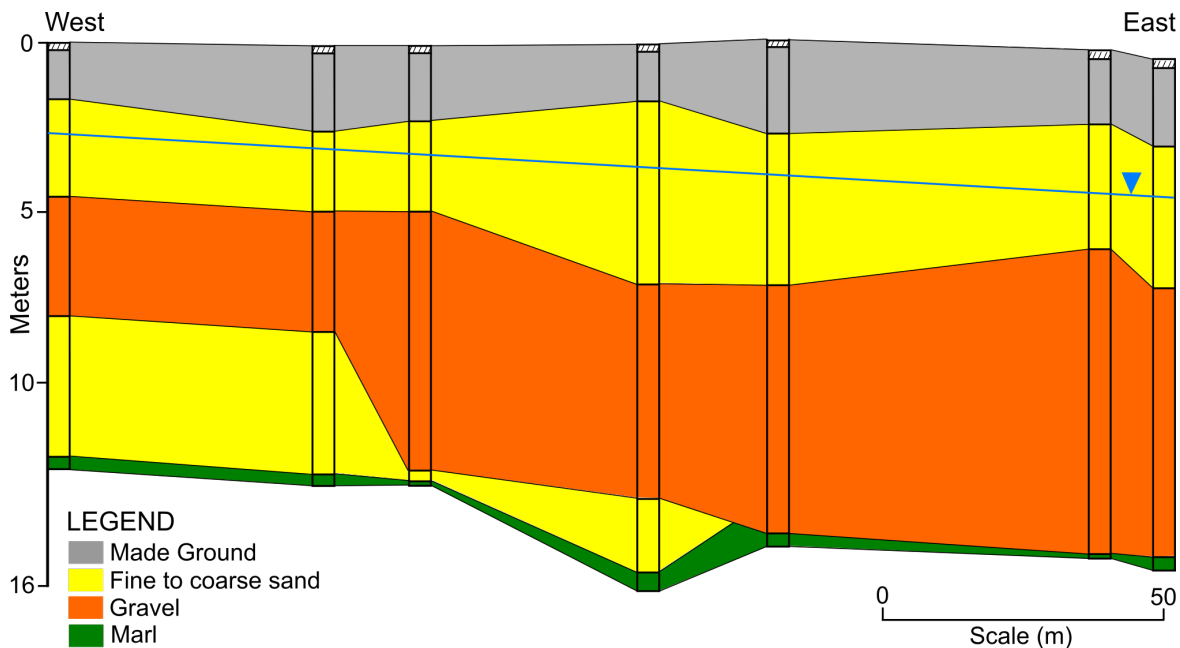


Figure 3.9: West to East schematic cross section of the local upper strata

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 at most places unconfined with a seasonal fluctuation between -2 to -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⁻¹. 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 m². The oil thicknesses measured in 120 wells ranged from a few centimetres to 2.5 m (Figure 3.10). 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, infiltration and different degradation stages, there is some spatial variability of the oil physical properties (Table 3.4). The oil viscosity and relative density have been measured on 25 oil samples, and the interfacial tension on 4 samples.

Table 3.4: Main physical properties of the oil

Product Relative Density (15°C)	0.85 to 0.88
Oil Viscosity (15°C)	90 to 115 cP
Oil/air Interfacial Tension	29 to 31 dynes.cm ⁻¹
Oil/water Interfacial Tension	16 to 18 dynes.cm ⁻¹

Long-term groundwater monitoring including analysis for total petroleum hydrocarbon (C6-C40 fraction) showed that the oil solubility is limited (oil concentration lower than 1 mg/L) 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, and to reduce the treatment cost of the extracted groundwater. The recovery system consists of 120 extraction wells connected to a collection system and central remediation unit with 40 m³ oil storage capacity. Ten other wells are distributed across the oil collection areas for monitoring purposes. After 18 months of extraction, 90 m³ 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.*, 2000), 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 (six months after start of remediation) and t_2 (eighteen 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; i.e., within 5% of the level measured at t_0 .

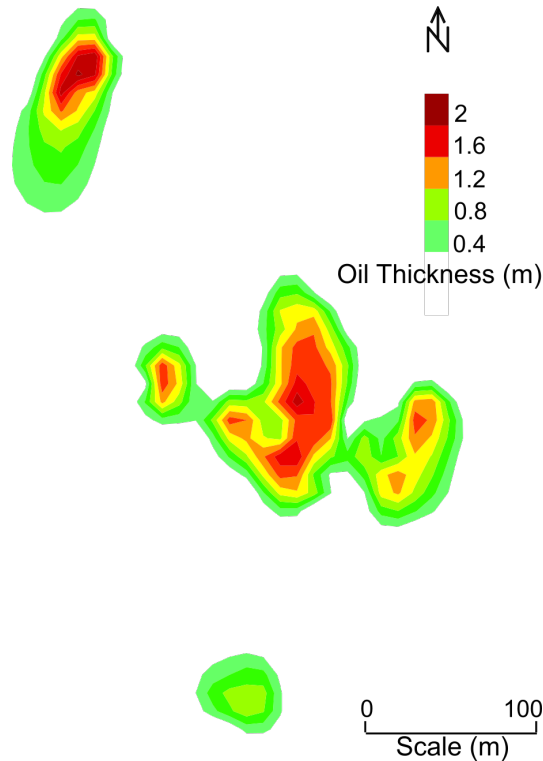


Figure 3.10: Distribution and thickness of the oil in meters using kriging interpolation at t_0

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 (pre-test) 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 two peristaltic pumps to remove only the oil phase. The flow rate of the pumps was set at $1.5 \text{ m}^3/\text{h}$ (in total).
- Monitoring the oil/air and oil/water interface levels during the time the oil thickness in a well recovered to, or nearly to, pre-test 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 five minutes 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 three days, the oil thickness in a well recovered to (or nearly to) pre-test 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 2.58). 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 2.61). For the modified Jacob and Lohman solution the two sides of Equation 2.72 are plotted and the sum of the squared residuals is automatically calculated. 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). The time cut-off has been visually estimated from the modified Bouwer and Rice, and for both the modified Cooper and Jacob and Lohman approaches, the time adjustment was estimated from Equation 2.73.

3.2.2 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. Analysis 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 if data can be interpreted using the modified Bouwer & 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 presented in Table 3.5.

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 3.5 describes the nature of the recharge of the well, based on the values of the J_{Ratio} . If the 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

Table 3.5: Synoptic view of the collected data

Summary of Comparisons between Drawdown and Oil Recharge to a Well (J_{Ratio})									
Linear Relation (Type 1) ($R_{J_{Ratio}}^2 > 0.8$)			Good Correlation (Type 2) ($0.8 > R_{J_{Ratio}}^2 > 0.5$)				Limited Relation (Type 3) ($R_{J_{Ratio}}^2 < 0.5$)		
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)	$J = -1$ (Type 3 b)	$J = -1$ (Type 3 c)	
80	58	6	11	41	1	6	82	4	

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 3.11). Finally, Type c represents data sets for which the J_{Ratio} is equal to -1, meaning that depth to the water is approximately constant during the test and no water enters the well after the oil is bailed. The analysis of the J_{Ratio} 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; Batu, 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).

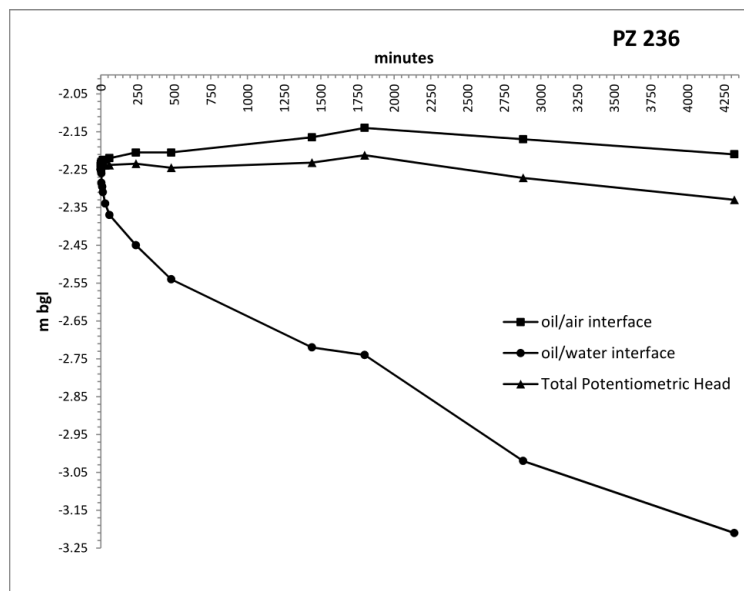


Figure 3.11: An example of oil/air and oil/water interfaces levels during the test (PZ236)

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 $s_o(t)$ 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 3.12). 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 *et al.* approaches can be explained by the difficulty of measuring the interface levels as emulsion 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 non-interpretable dataset. Figure 3.12 shows an example with data from PZ 222 at t_0 where the measurement error induced first a small decrease in and then a constant level of the oil/air interface at the beginning of the test.

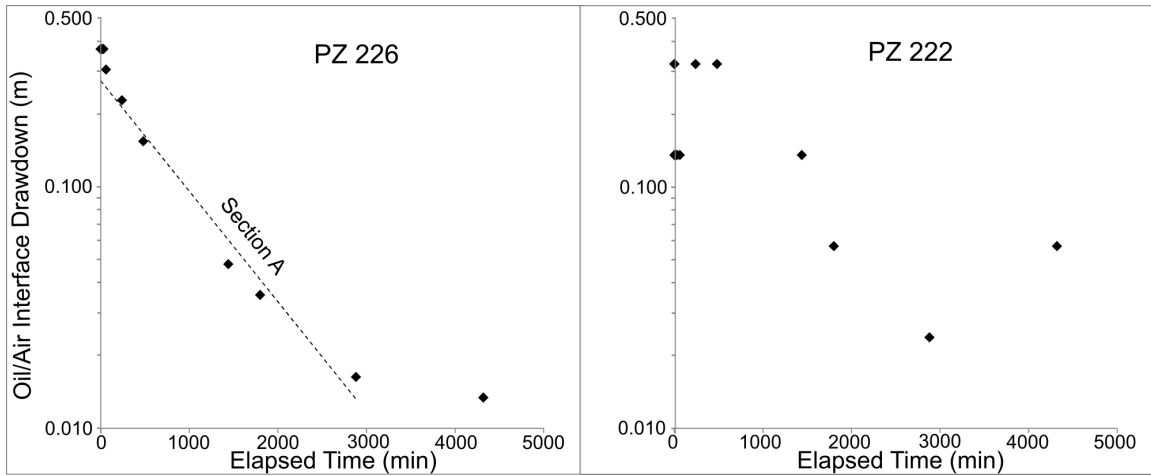


Figure 3.12: Bail-down test data sets for the piezometers PZ 226 and 222 at t_0

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 2.58 which presents the Bouwer and Rice modified solution (Kirkman, 2013), the drawdown considered ($s_{o(t)}$) is the oil/air interface drawdown.

Using the symbols from Figure 3.13, if $L_{o(t)}$ represents the oil thickness at time t , or $L_{o(t)} = b_1(t) + b_2(t)$, and $s'_{o(t)} = s_{o1(t)} + s_{o2(t)}$, then,

$$\frac{\delta L_{o(t)}}{\delta t} = -\frac{\delta s'_{o(t)}}{\delta t} \quad (3.2)$$

Where: $L_{o(t)}$	Oil thickness at time t	(m)
$b_1(t)$	Oil thickness at time t above the total potentiometric surface z_p	(m)
$b_2(t)$	Oil thickness at time t below the total potentiometric surface z_p	(m)
$s'_{o(t)}$	Total oil drawdown	(m)
$s_{o1(t)}$	Oil/air interface drawdown at time t	(m)
$s_{o2(t)}$	Oil/water interface drawdown at time t	(m)

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:

$$s_{o1(t)} = s'_{o(t)}(1 - \rho) \text{ and, } ds_{o1(t)} = ds'_{o(t)}(1 - \rho) = ds'_{o(t)}J \quad (3.3)$$

Therefore Equation 2.58 becomes,

$$T_o = \frac{r_c^2 \ln(R_e/r_w)}{-2Jt} \ln\left(\frac{s'_{o(t_0)}}{s'_{o(t)}}\right) \quad (3.4)$$

Where: T_o	Oil transmissivity	$(\text{m}^2 \cdot \text{s}^{-1})$
r_c	Well Radius	(m)
r_w	Casing Radius	(m)
R_e	Effective Well Radius	(m)

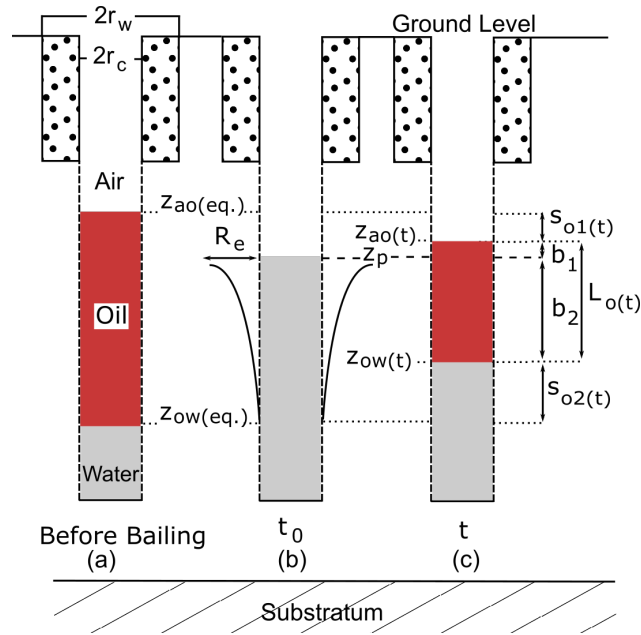


Figure 3.13: Geometry and symbols of partially penetrating wells in an oil/water system a) at equilibrium conditions, b) at the time t_0 and c) at the time t_1 after oil bailing

The input data is then the oil thickness instead of the oil/air interface level. Using this modified approach, which considers the total drawdown ($s'_{o(t)}$) of both oil and water, the quantity of data sets suitable for analysis increases to 202 (69.9%). Table 3.6 shows the percentage of data which can be interpreted using $s_{o(t)}$ or $s'_{o(t)}$ drawdown, based on the J_{Ratio} correlation and on the nature of recharge to the wells.

Table 3.6 should be read as follows: 67% of the 80 bail-down tests (Type 1 a) for which i) the J_{Ratio} presents a good correlation ($R_{J_{Ratio}}^2 > 0.8$), and ii) the total potentiometric

Table 3.6: Percentage of the Data Sets Suitable for Analytical Interpretation using $s_{o(t)}$ or $s'_{o(t)}$

	$(R_{J_{Ratio}}^2 > 0.8)$			$(0.8 > R_{J_{Ratio}}^2 > 0.5)$			$(R_{J_{Ratio}}^2 < 0.5)$		
	$J = -(1 - \rho_o)$ (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)	$J = -1$ (Type 3 b)	$J = -1$ (Type 3 c)
Number of tests	80	58	6	11	41	1	6	82	4
Percentage of tests that can be interpreted using $s_{o(t)}$	67	34	0	9	19	0	0	2	0
Percentage of tests that can be interpreted using $s'_{o(t)}$	100	81	17	91	66	0	33	40	50

surface remains constant during the test $J = -(1 - \rho_o)$, can be interpreted using $s_{o(t)}$. The percentage of bail-down tests which can be interpreted using $s'_{o(t)}$ for the same bail-down type (Type 1 a) 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 $J = -(1 - \rho_o)$, 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 ($T_{B\&R} = 3.8 \times 10^{-5}$ m²/min, $T_{Coop.} = 3.0 \times 10^{-5}$ m²/min and $T_{Jacob} = 3.9 \times 10^{-5}$ 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 3.14 shows that $T_{B\&R}$ and $T_{Coop.}$ are well correlated. The grey 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.

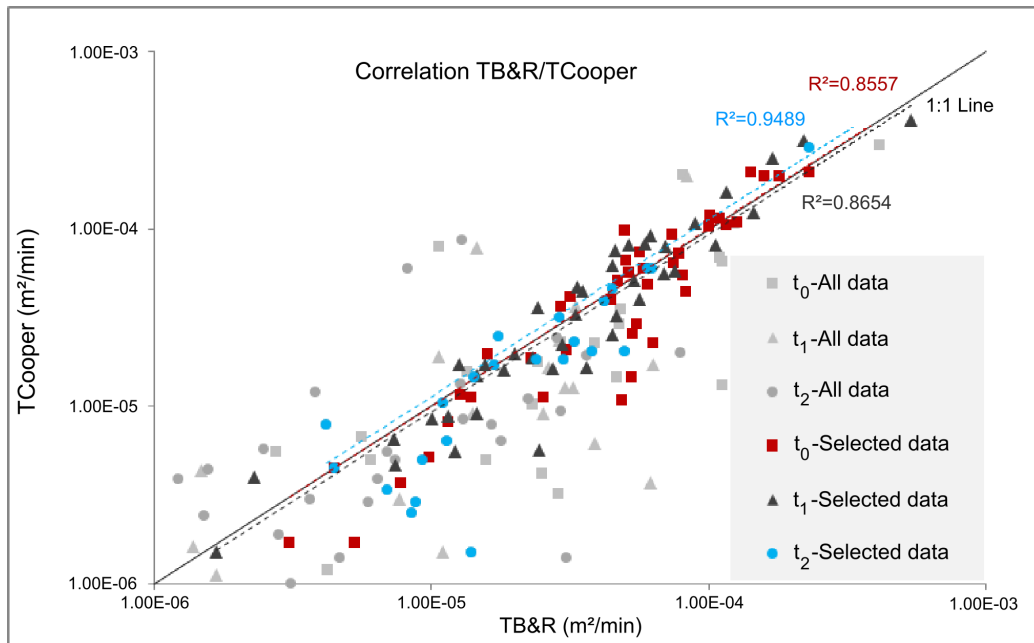


Figure 3.14: Correlation between the oil transmissivity values estimated by the modified Bouwer and Rice approach and by the modified Cooper *et al.* approach using $s'_{o(t)}$. Selected data correspond to from Type 1 and 2 for which $R_{J_{Ratio}}^2 > 0.5$

Figure 3.15 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 3.14).

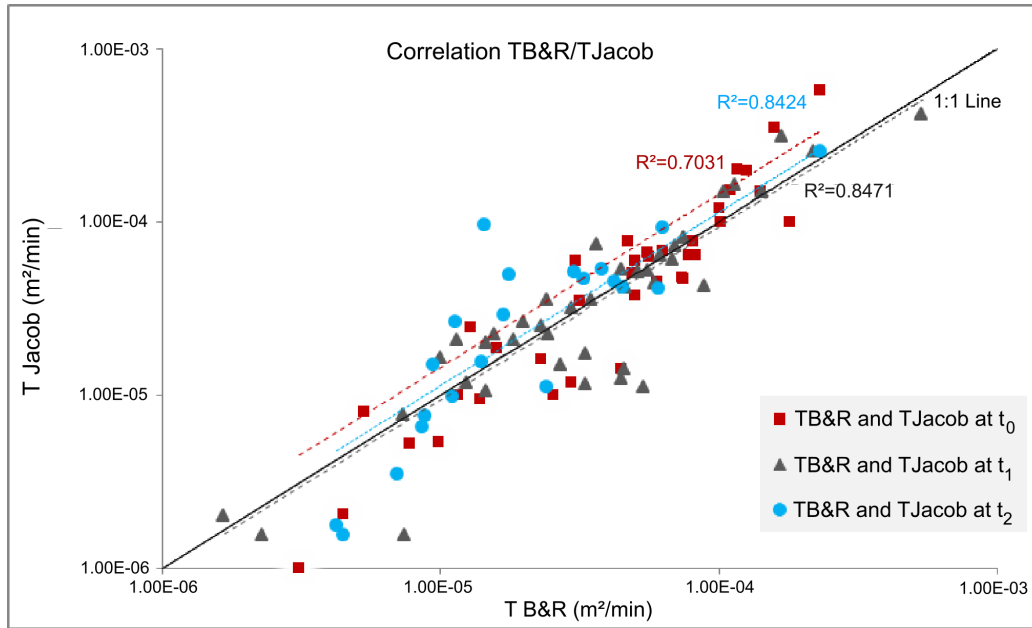


Figure 3.15: Correlation between the oil transmissivity values estimated by the modified Bouwer and Rice approach and by the modified Jacob and Lohman approach using $s'_{o(t)}$

This analysis gives a reasonable indication that the oil transmissivity values obtained with one of these approaches ($T_{B\&R}$, $T_{Coop.}$ 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 3.16).

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 3.17, 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.

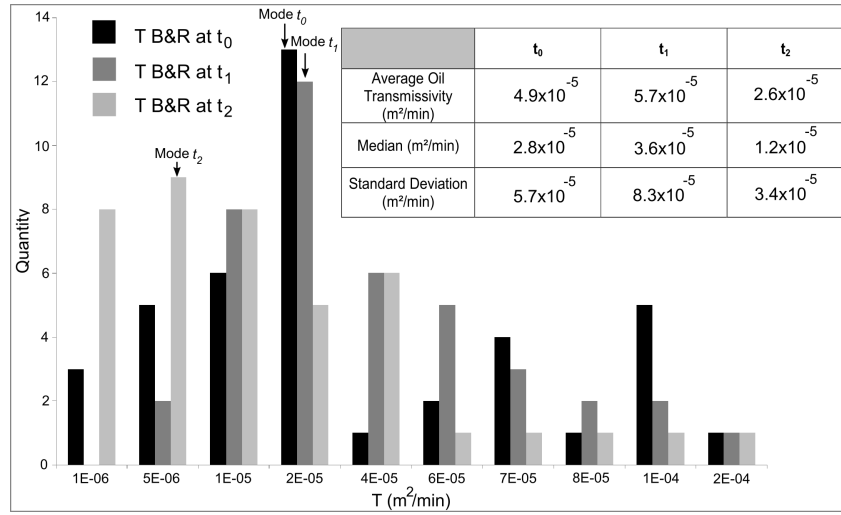


Figure 3.16: Oil transmissivity values and main statistics before (t_0), 6 months after (t_1) and 18 months after (t_2) start of remediation

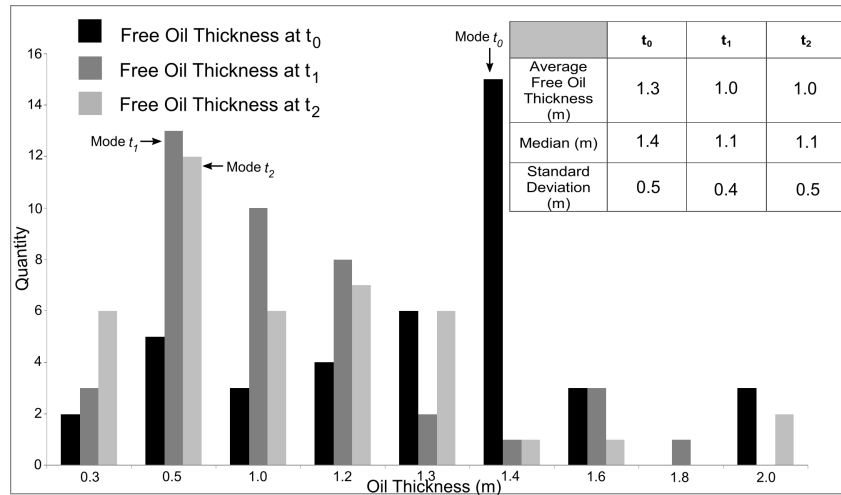


Figure 3.17: Oil thickness in the wells before (t_0), 6 months (t_1) after 18 months after (t_2) start of remediation

The trends shown on Figures 3.16 and 3.17 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 transmissivity and the oil thickness measured in the wells is clearly shown by Figure 3.18 which superimposes the oil thickness distribution and the calculated oil transmissivity values ($T_{B\&R}$) at t_0 and t_2 .

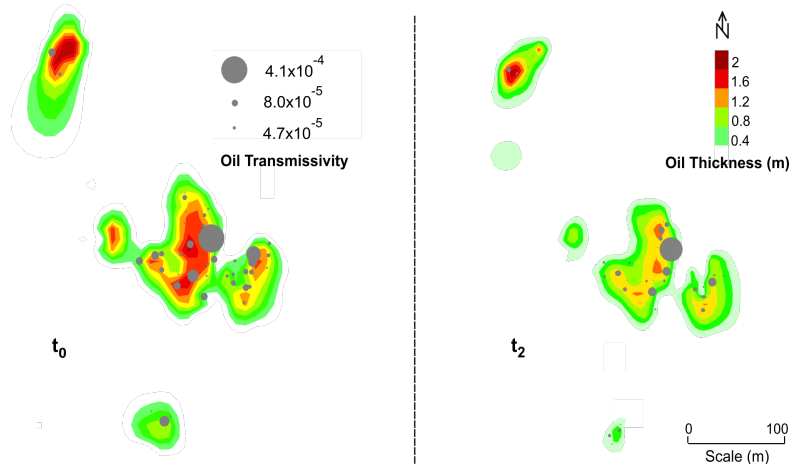


Figure 3.18: Oil transmissivity distribution (at t_0 and t_2) and oil thickness in wells (at t_0 and t_2)

3.2.3 Discussion and Conclusions

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, i.e. sand and coarse sand, 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 by placing a pressure transducer below the oil/water interface 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 $s'_{o(t)}$ 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 & Rice, modified Cooper et al., and modified Jacob and Lohman) that are based on different assumptions and boundary conditions, 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 is not feasible across a large project site. It can therefore be concluded 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 2.2.2 (drawdown assumption, pseudo steady-state) does not appear to be a basis for restricting the use of these analytical solutions as suggested by Batu (2013). The poor sensitivity to these assumptions may be explained by the large 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 only slightly affects the oil level in the formation, therefore: i) the true drawdown in the formation can be considered as negligible regard to the drawdown in the well and, ii) oil movement in the formation can be assumed to be pseudo steady-state.

Secondly, this study shows that the simplifying assumption made by 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 & 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 behaviour at the site, but not critical to apply Bouwer & Rice method. 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 in these wells different behaviours. 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 and heavy lubricating oil. Wells with less dense and less viscous products like fuels will respond and equilibrate faster; and will impact some of the underlying assumptions for analysing bail-down tests on those sites.

Finally, in this study 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 to the oil thickness. Consequently, thin coarse soils may have oil transmissivities that are orders of magnitude higher than thick finer soils (Huntley *et al.*, 1992). There is an overall decrease in both oil transmissivity and thickness over the whole site over the time. But, as explained above, these two parameters are not correlated, at any time.

The results obtained at the laboratory and field scales suggest that the bail-down tests provide a reliable approach to estimate the oil transmissivity, and thus the oil mobility in a formation. This tool can therefore be used as a basis for a detailed characterization of the distributed properties of the oil body at the field scale. The outcome of this detailed characterization should be the basis to better target the most productive areas and thus, to optimize the oil recovery design.

Chapter 4

Groundwater Table Fluctuation

The saturated zone thickness in an unconfined aquifer varies over time mainly due to infiltration of precipitation and, secondly, to atmospheric pressure changes. The variation in water head can be followed by measuring the air/water interface level in monitoring wells. When oil is present and forms a free oil layer that can be measured in a monitoring well, the groundwater fluctuation may have a significant impact on its apparent thickness. It is an important phenomenon that may lead i) to significant discrepancies between measured oil thickness in monitoring wells and oil volume in soil, and ii) a misinterpretation of the oil distribution and mobility in the adjacent formation. Marinelli and Durnford (1996) have listed some common, apparent discrepancies between the oil measured in the wells and the oil distribution in the adjacent formation (Mayer and Hassanizadeh, 2005):

- Monitoring wells contain no oil although soil sampling indicates presence of considerable amount of oil in the adjacent formation in the vadose zone or below the water table.
- Oil thickness in a well increases when the water table falls and decreases when the water table rises.
- Sudden appearances or disappearance of observable oil in wells.
- Oil completely disappears from monitoring wells when the water table level drops below historic minimum.

These phenomena are well known but rarely assessed and used when investigating a contaminated site. A more sophisticated analysis would allow for the estimation of key parameters such as the oil thickness and volume in the aquifer, and the hydraulic oil conductivity. Such analysis would present the advantage that the groundwater table and the oil thickness in wells are parameters to easily measure over the time and over large areas.

Kemblowski and Chiang (1990) explained the mechanism of the oil thickness fluctuation in the monitoring wells. They considered both the equilibrium and the non-equilibrium

conditions to explain the field observations as, for example, oil increasing in wells when groundwater table falls. When the equilibrium conditions are satisfied, it means that the groundwater interface falling or rising is slow enough to allow the fluids in the well, in the gravel pack and in the adjacent formation to equilibrate. In this case, and assuming no vertical oil movement in the formation, Kemblowski and Chiang (1990) suggest three different scenarios.

- The groundwater level is decreasing and no oil is trapped below the oil/water interface. This happens at the beginning of a release or when groundwater drops to a very low historic level. In this case, the oil overlying the water table will follow the movement of the water table and will be trapped as residual in the non-saturated zone. The oil thickness in the monitoring well will decrease as the amount of mobile oil will decrease.
- The groundwater level is decreasing and oil is trapped below the oil/water interface due to previous groundwater table fluctuations. In this case, the measured oil thickness in the monitoring well may increase as the oil previously trapped in the saturated zone will be released into the well.
- The groundwater level is increasing. In this case, some oil is trapped in the saturated zone and the measured oil thickness decreases.

If the piezometric head variations are too fast, the above equilibrium conditions cannot be satisfied. Kemblowski and Chiang (1990) suggest that when the groundwater table is moving in the aquifer, the monitoring well will act as a conduit for the fluids. The water pushes the oil up within the well. The oil then flows radially into the gravel pack and the formation due to the pressure gradient. As a result, the oil thickness in the monitoring wells will decrease. When groundwater table will decrease, oil previously trapped will become mobile as already described. This lowering of the oil/water interface in the well will allow the oil from the gravel pack and from the formation to flow into the well. Therefore, the oil thickness will increase in the well.

Aral and Liao (2002) further investigated the transient conditions and proposed a model for oil thickness fluctuations in a monitoring well due to groundwater table movements. A significant difference with Kemblowski and Chiang (1990) description is that Aral and Liao (2002) does not consider the role of the residual oil saturations to explain the oil thickness fluctuation in the well. Oil thickness fluctuations in the well are only explained by pressure differences between the well and the formation that allows fluids to flow. Due to piezometric head variations, the oil in the well can be positioned at different levels as compared to the oil in the formation. As an example, Figure 4.1(a) shows a situation where the total potentiometric surface is above the oil layer which leads to no oil in the well. Figure 4.1(b) shows a situation where the total potentiometric heads dropped significantly below the oil layer in the formation (which moves significantly slower than the fluid in the wells). In this case, oil will flow from the formation to the well. After a certain period of time, oil thickness in the well will be much larger than the oil layer thickness in the formation.

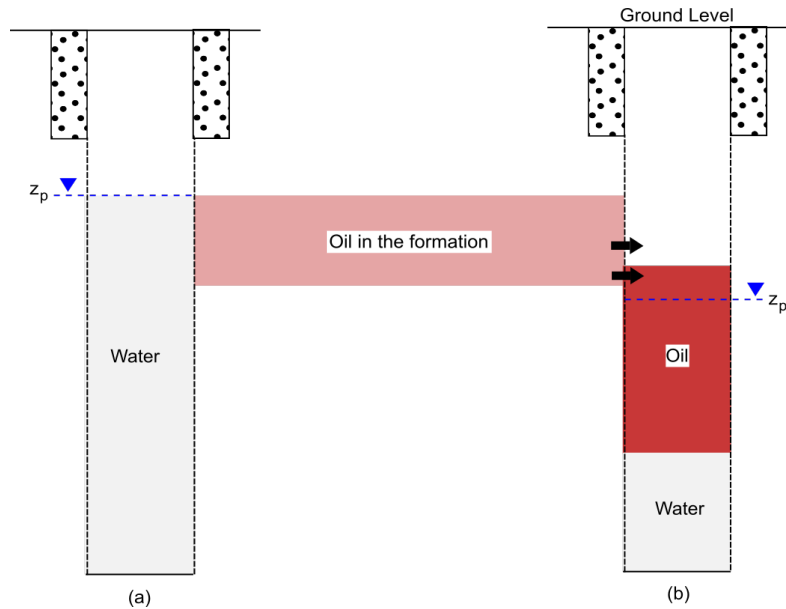


Figure 4.1: Schematic view of fluids level in monitoring well considering different levels of z_p compared to the oil layer position in the formation. (a) z_p is higher than the top of the oil layer in the formation, no oil is present in the well. (b) z_p is lower than the oil layer in the formation, oil is flowing from the formation to the well (black arrow)

The objectives of this section are to present i) the impact of the groundwater table variation on oil thickness in monitoring wells that have been measured manually on a long-term, and automatically for shorter periods of time, ii) a comparison of oil thickness fluctuation in monitoring wells located in areas where the oil layer is confined and in others where it is unconfined and, iii) an application of Aral and Liao (2002) model with some modifications for estimating the oil layer thickness in the formation and the hydraulic oil conductivity, for both confined and unconfined oil layers.

The Chapter is organized as follow. Section 4.1 presents the theoretical background used to develop the proposed model. Section 4.2 presents the methods applied for the short-term and long-term measurements of the groundwater table fluctuation and of the oil thickness. This section also includes a description of the nature of the formation around the monitoring wells, along with the position of the oil phase inferred from organoleptic and analytical informations. Section 4.3 presents first a detailed description of the oil thickness fluctuations in the wells for confined and unconfined conditions. Then, it presents the application of the model to different field measurements. Finally, Section 4.4 summarizes the key outcomes of the study and further discusses the conclusions.

4.1 Theory

Aral and Liao (2002) proposed a groundwater fluctuation model with a simplifying assumption that considers a homogeneous hydraulic oil conductivity over the oil layer in the for-

mation. Aral and Liao (2002)'s work shows that their model agrees well with measured oil thickness in monitoring wells under groundwater fluctuation conditions in their laboratory scale study.

The approach proposed in our study is described below for unconfined and confined (or semi-confined) oil layers and is based on some elements taken from Aral and Liao (2002) model but with modifications and different notations that require a full description. Key modifications are:

- Due to a highly permeable formation present in the study site, the groundwater is assumed to equilibrate rapidly (hydrostatic condition within the whole aquifer and between the aquifer and the well in the water phase).
- The model considers a homogeneous oil layer in the formation. The model accounts for oil saturation variations from S_{ors} to $S_{o(max)}$.
- The model has been modified for a confined oil layer.

The situation considered is a well in a formation where an homogenous oil layer of constant specific volume (m^3 of oil over 1 m^2) is present. In the first case, the hydraulic oil conductivity is assumed to be at the same value anywhere in the oil layer. Due to the hydrostatic pressure field, the water in the well is assumed to be in equilibrium with the water in the formation. The oil layer is moving up and down in the formation due to groundwater table fluctuation. This vertical oil mobility leads to the presence of oil at residual saturation above and below the oil layer. At equilibrium condition between the well and the formation, the oil layer and the oil in the well are at the same level and no flow occurs.

When the groundwater table fluctuates, it triggers non-equilibrium conditions between the oil in the well and the oil layer in the formation. The situation can be described as shown in Figure 4.2, using, for simplification, a layer of mobile oil of known and permanent characteristics. Two main conditions can occur. In Figure 4.2(a), the height of the oil-air interface (z_{oa}) is lower than the top of the oil layer in the formation (N_{oa}). Therefore, oil can move from the formation to the well. The oil flow from the formation to the well is represented by the black arrows, and the hydraulic oil conductivity is noted K_o . Also in Figure 4.2(a), the pressure in the two fluids within the formation is illustrated (assuming the pressure in the phases is close to hydrostatic pressure fields, given the very slow velocity of the phases), and it can be seen that the oil pressure at the bottom of the oil layer is higher than the water pressure, and thus the oil layer will move downward. The illustration assumes that the vertical pressure distribution is not impacted by the residual oil saturation. Figure 4.2(b) is the reverse situation with the oil interface z_{oa} in the well being higher than the top of the oil layer in the formation. The oil flows from the well to the formation. The top part of the oil will flow in the unsaturated zone where oil and water saturations are at a residual value. This component of the hydraulic oil conductivity is noted K_a and is represented by the grey arrow on the Figure 4.2(b). The lower part of the oil in the well will flow into the oil layer present in the formation where the hydraulic oil conductivity is K_o .

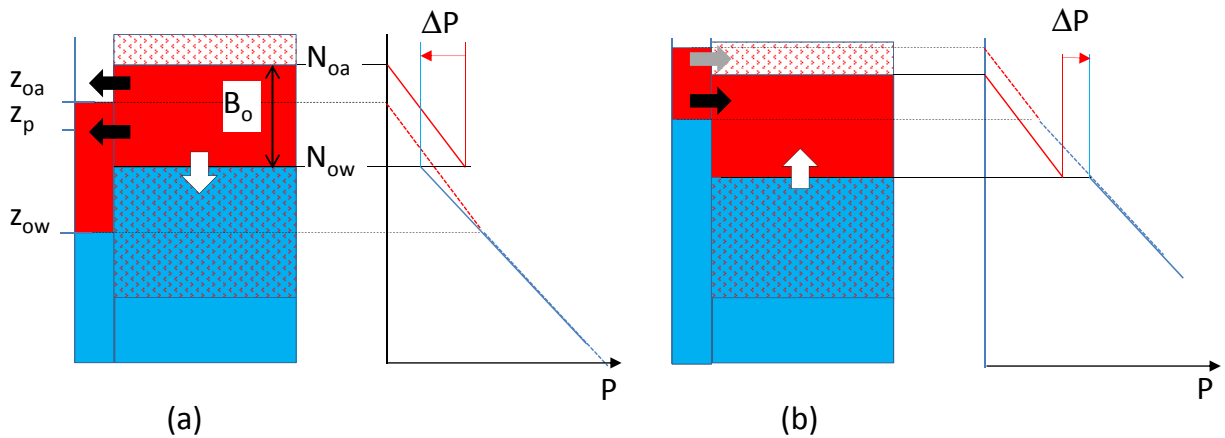


Figure 4.2: Schematic view of fluids position in a well and the adjacent formation considering an unconfined oil layer, along with i) pressures in each phase and, ii) oil flow direction. The water is represented in blue, mobile oil in red, and the residual oil in red pattern. The black and grey arrows show potential movement of oil between the well and the formation, and the white arrows show the potential vertical movement of the oil in the formation. z represents a level measured in the well and N represents a level measured in the formation. To the right of each view, the fluid pressures in the well are illustrated with dotted lines, and the fluid pressures in the formation are illustrated with solid lines

To calculate the fluctuations in both the well and the aquifer, the following assumptions are made:

1. The pressure equilibrates much faster in the water phase than in the oil. The pressure at the bottom of the well is thus considered to be equivalent to the one at the same elevation in the aquifer (inducing blue dotted and solid line to be overlaid in Figure 4.2);
2. As historical groundwater movements may have reached both higher and lower levels than the current position, a presence of residual oil below and above the mobile oil layer is considered;
3. The specific volume of the mobile oil is considered to be constant: this arises from the previous assumption of the presence of residual oil and from the negligible volume of oil in the well compared to the aquifer;
4. The presence of air on top of the oil thus imposing atmospheric pressure on top of the oil layer;
5. A homogeneous value of the oil hydraulic conductivity in the oil layer, thus assuming a constant capillary pressure over the oil layer;

The above assumptions 1 and 2 are different from the work of Aral and Liao (2002).

4.1.1 Unconfined Oil Layer

The vertical movement of the mobile oil layer can be described with the classical Darcy's law:

$$v_o = -K_o \frac{\Delta H}{B_o} \quad (4.1)$$

where: v_o Vertical velocity of the oil layer in vertical direction (m.s⁻¹)
 K_o Hydraulic oil conductivity of the medium (m.s⁻¹)
 ΔH Head difference between the oil and the water (m)
 B_o Thickness of mobile oil in the formation (m)

In Equation 4.1, K_o includes the relative permeability to oil for the considered oil saturation.

The head difference between the oil and the water is calculated at the bottom of the oil phase as shown in Figure 4.2. In order to have a movement of the oil, the head difference shall be higher than the entry capillary pressure (Aral and Liao, 2002), therefore:

$$\Delta H = (z_p - N_{ow}) - \rho_r B_o - h_c \quad (4.2)$$

where: h_c Capillary pressure head (m)
 ρ_r Relative oil density (-)
 z_p Total piezometric head (expressed as water) (m)
 N_{ow} Level of the bottom of the oil layer in the formation (m)

Therefore we get

$$dN_{oa} = dN_{ow} = -K_o \frac{\Delta H}{B_o} dt \quad (4.3)$$

Due to the assumption of rapid equilibrium, the exchange of water between the well and the aquifer is not calculated. The exchange of oil between the well and the aquifer can be divided in two situations. First, for case (a), i.e., when the top of the oil layer in the well is lower than in the aquifer ($z_{oa} < N_{oa}$) the exchange can be calculated with the classical flow of a fluid from an aquifer to a well (assuming that streamlines remain horizontal, even if the air-oil interface near the well is not horizontal) using Thiem (1906), as follows:

$$q = \frac{2\pi K_o B_o (N_{oa} - z_{oa})}{\ln(R_e/r_w)} = A(N_{oa} - z_{oa}) \quad (4.4)$$

where: R_e Effective Well Radius (m)
 r_w Casing Radius (m)

Using of Thiem's equation implies that the following assumptions are satisfied:

1. Flow lines to the well are horizontal.
2. Flow to the well is steady-state.
3. Aquifer is homogeneous and isotrope.
4. The horizontal component of the velocity is constant at any point across the flow section.
5. The vertical component of the velocity is negligible when compared to the horizontal component of the velocity.
6. Darcy's law can be applied.
7. The potentiometric surface level in the aquifer is equal to the water level in the well, and the well influence is negligible at a constant distance R_e from the well.

Based on the outcomes of Chapter 3, it has been shown that, for the conditions of this study, when the oil is bailed out during a bail-down test, i) the drawdown in the formation is very limited, and ii) the return flow to the well can be considered steady-state . Therefore, the above assumptions shall be satisfied.

For case describes in Figure 4.2(b) , when the oil surface in the well is higher than in the aquifer, the relation is different since part of the oil is flowing into the unsaturated portion of the aquifer. This can be written as:

$$q = \frac{2\pi[K_o \min(N_{oa} - z_{oa}, B_o) + K_a(z_{oa} - N_{oa})](z_{oa} - N_{oa})}{\ln(R_e/r_w)} \quad (4.5)$$

K_a is the hydraulic oil conductivity of the aquifer filled with air and both oil and water at residual saturation, therefore it is supposed to be higher than K_o . The lower value between B_o and $(N_{oa} - z_{ow})$ is used to consider only the thickness of the contact between the oil in the well and the oil in the aquifer.

During the oil exchange between the well and the formation we consider that the total piezometric head remains equal to the groundwater one (z_p) due to fast water exchanges, that gives:

$$z_p = z_{ow} + \rho_r(z_{oa} - z_{ow}) = (1 - \rho_r)z_{ow} + \rho_r z_{oa} \quad (4.6)$$

with,

$$dz_p = (1 - \rho_r)dz_{ow} + \rho_r dz_{oa} = 0 \quad (4.7)$$

and,

$$d(z_{oa} - z_{ow}) = \frac{q}{\pi r_c^2} \quad (4.8)$$

The exchanged discharge q comes from the whole height of oil in the well but, due to the equilibrium cited above, the variations of z_{oa} and z_{ow} are different:

$$dz_{oa} = (1 - \rho_r) \frac{A}{\pi r_c^2} (N_{oa} - z_{oa}) dt \quad (4.9)$$

$$dz_{ow} = dz_{oa} \frac{\rho_r}{(1 - \rho_r)} \quad (4.10)$$

where: r_c Radius of the well (m)

These equations can be solved iteratively by an explicit method considering a series of steady state conditions, requiring very short time steps.

The above equations make the assumption of a constant residual and maximum oil content in the porous medium. However, the residual oil content in the non-saturated zone (S_{orv}) can be lower than in the saturated zone (S_{ors}). Moreover, depending on the characteristic of the medium, the maximum saturation ($S_{o(max)}(z)$) can vary with elevation. In the presence of such variations, the Equation 4.3 must be written slightly differently:

$$dN_{ow} = -K_o \frac{\Delta H}{B_o} dt \quad (4.11)$$

and considering a constant specific volume,

$$dN_{oa} = dN_{ow} (S_{o(max)}(N_{ow}) - S_{ors}) / (S_{o(max)}(N_{oa}) - S_{orv}) \quad (4.12)$$

In that case B_o also varies with time.

4.1.2 Confined or Semi-Confined Oil Layer

The non-equilibrium situation for a confined oil layer can be described as in Figure 4.3. In a strictly confined medium, i.e., when the pressure head is always higher than the bottom of the confining medium, the oil cannot move. Thus, the only process that will occur is the variation of water and oil levels in the well to equilibrate the variations of head. In that case we have:

$$dz_{ow} = dz_{oa} = dz_p \quad (4.13)$$

However this case is not so common and most of the concerned wells include a confining layer of thickness smaller than the oil thickness. Several cases, including confinement or semi-confinement, can occur depending on the relative position of the confining layer and the top and bottom of the oil. In order to analyze these different cases the confining was modeled by assigning a low permeability to the concerned layer, and modifying the unconfined equations.

In this situation, the hydraulic oil conductivity is not homogeneous within the oil layer. To describe this situation, the model developed for unconfined conditions has been modified to account for a vertical hydraulic oil conductivity (K_{ov}) and an horizontal hydraulic oil conductivity (K_{oh}) in a layered system.

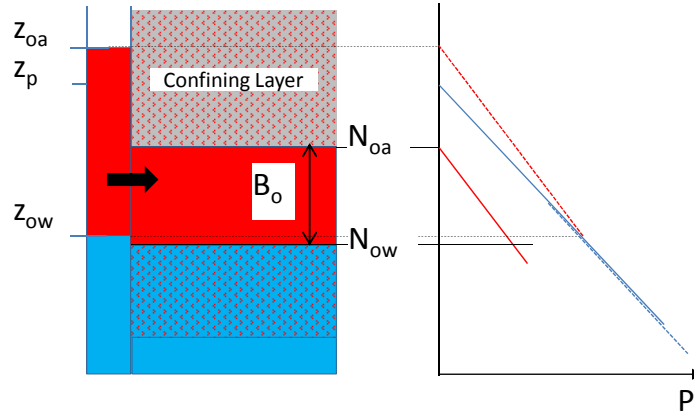


Figure 4.3: Schematic view of fluids position in a well and the adjacent formation considering a confined oil layer, along with i) pressures in each phase and, ii) oil flow direction. The water is represented in blue, mobile oil in red, and the residual oil in red pattern. The black arrow shows potential movement of oil between the well and the formation. z represents a level measured in the well and N represents a level measured in the formation. To the right of each view, the fluid pressures in the well are illustrated with dotted lines, and the fluid pressures in the formation are illustrated with solid lines

For the vertical oil movement (streamlines perpendicular to stratification) we simply have:

$$K_{ov} = \frac{N_{oa} - N_{ow}}{\sum l_i / K_i} \quad (4.14)$$

where: K_{ov} Vertical hydraulic oil conductivity (m.d⁻¹)
 l_i Thickness of each layer included in the oil between N_{oa} and N_{ow} (m)
 K_i Hydraulic oil conductivity of each layer included in the oil between N_{oa} and N_{ow} (m.d⁻¹)

As the hydraulic oil conductivity is generally low in silt layers, this will often lead to very slow vertical movements of the oil in the aquifer. For the flow between the well and the aquifer the averaging is different (streamlines parallel to stratification):

$$K_{oh} = \frac{\sum l_i K_i}{\min(N_{oa} - z_{ow}, B_o)} \quad (4.15)$$

Then K_{ov} is inserted in Equation 4.1 and K_{oh} in Equations 4.4 and 4.5 replacing K_o .

Here a thin layer of sand (therefore with high permeability) at any depth can significantly increase the exchange between the well and the aquifer. It can be noted that if the hydraulic oil conductivity is homogeneous, these equations lead to the same value of K_o and thus to the same equations as in the unconfined case. In order to keep the consistency with the unconfined approach, even with a very low oil content in the silt layers, the top of the oil in the aquifer (N_{oa}) is considered to be at atmospheric pressure (as in Figure 4.2).

4.1.3 Basic Examples

In order to illustrate the role of the variation of the piezometric head on the evolution of the different levels in the well, two basic examples were considered. For both examples, in order to simplify, the oil was not mobile in the aquifer. The first one (Figure 4.4(a)), represent a peak of the piezometric head. In that case we see that at the beginning of the z_p rise, the top of the oil in the well (z_{oa}) is rising, becoming higher than N_{oa} . This leads to a flow from the well to the aquifer, which depletes most of the oil from below z_p or a significant increase of z_{ow} . For the second example (Figure 4.4(b)), there is a constant increase of z_p , and in that case we see that the flow from the well to the aquifer leads to thinning of the oil layer in this well, and, finally to the absence of oil in the well. At this stage, by evidence all levels are equal.

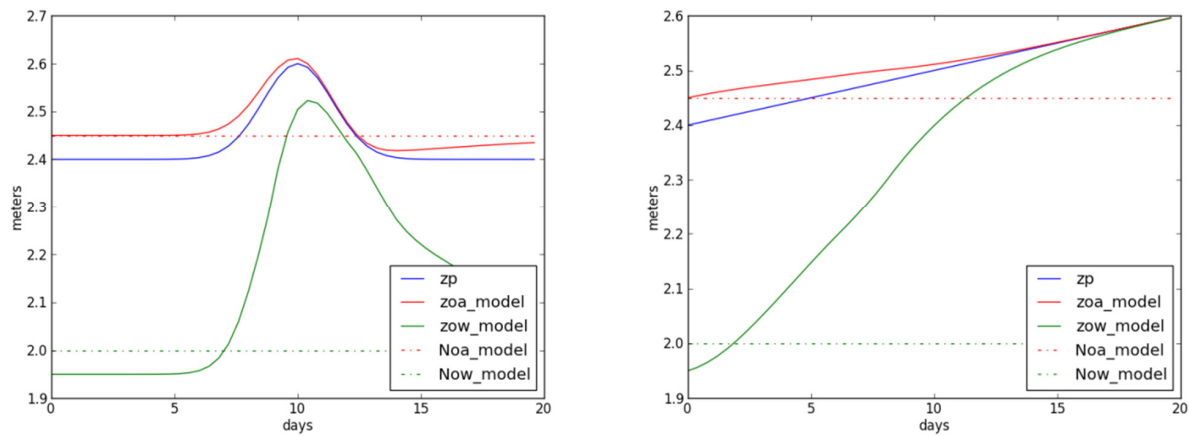


Figure 4.4: Temporal evolution of the interfaces for basic case. a) A peak in piezometric head, hence b) slowly rising piezometric head. For both cases the oil is set to be immobile in the aquifer

4.2 Material and Methods

This study has been performed on the site already presented in Section 3.2. This site has a long history of oil being affected by groundwater fluctuation, with oil present in the subsurface since more than 10 years. The oil thicknesses in monitoring wells have been measured on a regular basis, from March 2011 to December 2015. These measurements took place in eleven wells, two outside the factory building and the other nine inside (Figure 4.5).

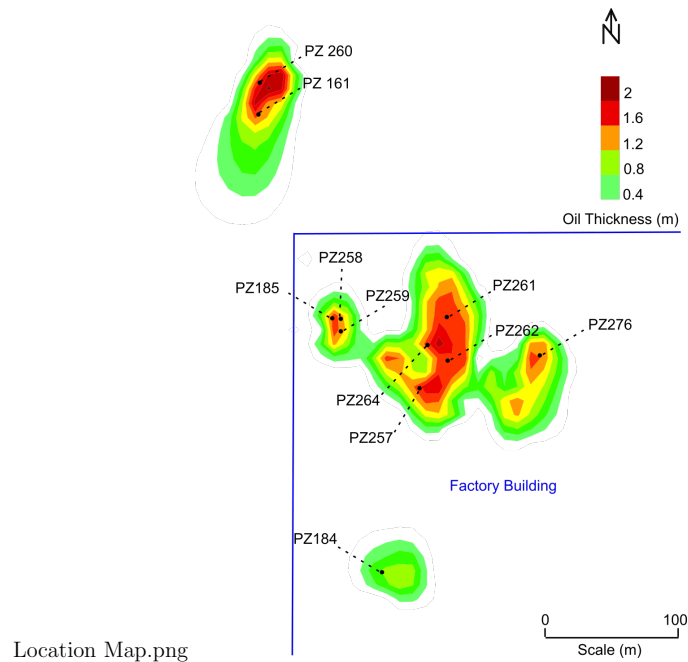


Figure 4.5: Monitoring wells locations and oil distribution using kriging interpolation in October 2011

The selected wells were all dedicated to monitoring purposes and no oil recovery occurred in these wells over that period. They have been selected to represent different types of soil from silty layer to sandy/gravel layer. The well logs are presented Figure 4.6.

Based on the borehole logs and on the review of the field notes, the approximate location of the oil vertical distribution has been determined from the organoleptic indication during the drilling. The presence of oil confirmed by the oil smell and visual observations (e.g.: colour change) has been reported on the logs of the Figure 4.6 (red marks). It can be noticed that the oil, when present in the formation is first encountered approximately 2.3 to 2.4 m below ground level. In addition of the organoleptic observations, an undisturbed soil core boring has been completed at 0.30 m of the monitoring well PZ260. The oil content of each 0.50 m of soil has been analyzed by an accredited laboratory (Annex C). These analyses confirmed the organoleptic observations and allowed the vertical oil saturation distribution to be determined, as shown on Figure 4.6.

The wells were sorted based on the grain size distribution and heterogeneity of the adjacent formation at the depth where oil is present. The following categories have been defined.

- Category 1 groups the wells located in areas where the adjacent formation is fairly homogeneous with a grain-size distribution varying from gravel to coarse sand.
- Category 2 groups the wells located in areas where the adjacent formation presents a wide range of grain-size distribution with fine or silty sand layers embedded between coarser sand layers. Table 4.1 presents the category for each the monitoring well.

Oil/air and oil/water interface levels were manually measured on a quarterly basis using an interface probe (model SOLINST SI30). In parallel, a well from the category 1 (PZ262)

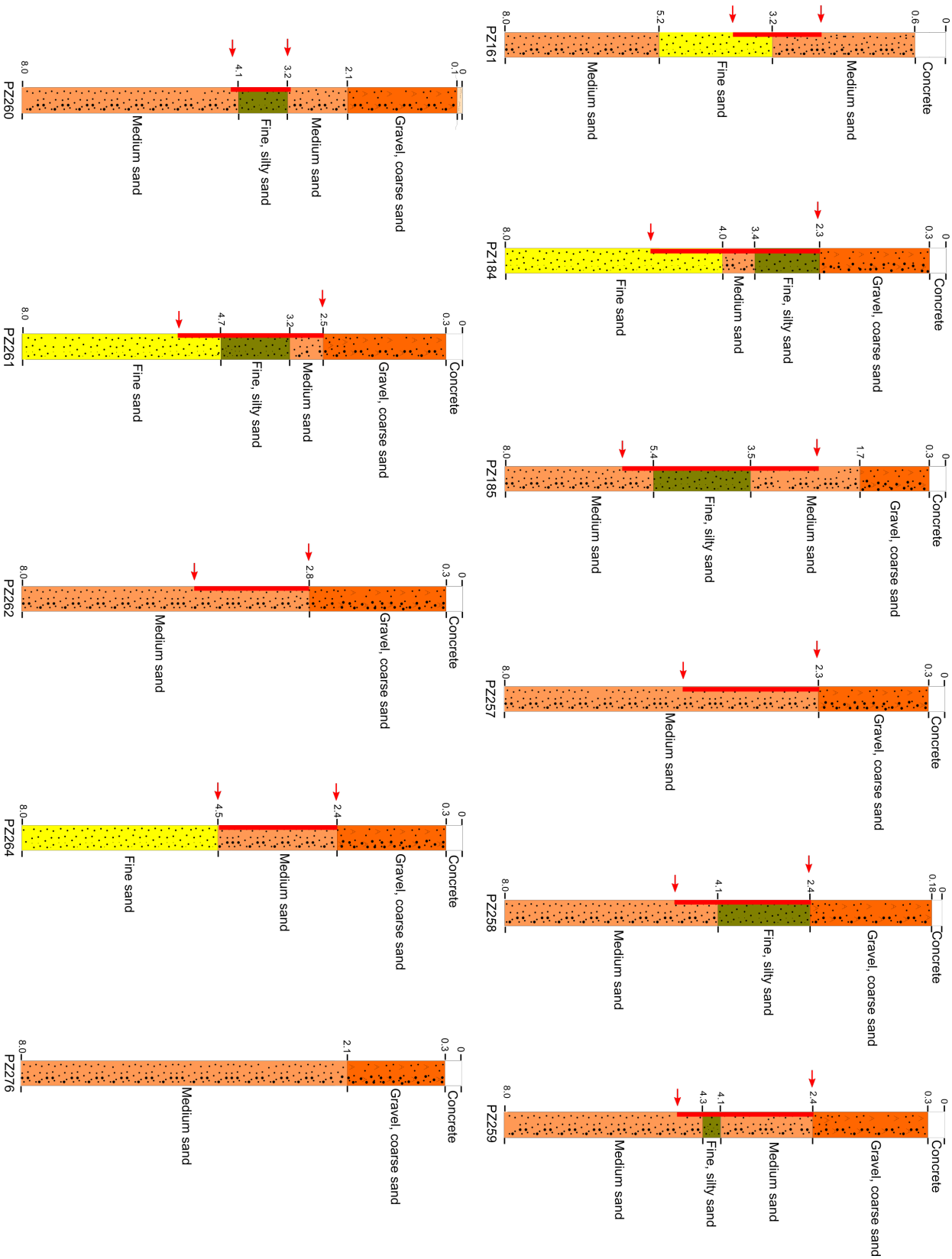


Figure 4.6: Well logs with geologic interpretation of the 11 monitoring wells used to follow the oil/air and oil/water interfaces from March 2011 to December 2015. The arrows and red marks indicate the presence of oil observed during the drilling (organoleptic indications)

Table 4.1: Monitoring wells classification based on the grain size distribution of the adjacent formation

Monitoring Wells	Category 1	Category 2
PZ161		X
PZ184		X
PZ185		X
PZ257	X	
PZ258		X
PZ259		X
PZ260		X
PZ261		X
PZ262	X	
PZ264	X	
PZ276	X	

and a well from the category 2 (PZ260) were targeted to measure the interface levels with automatic pressure probes. The automatic data acquisition has been made using three interface probes (model Rugged TROLL 100). The protocol followed the method described in Section 2.2. Three automatic pressure probes were installed in monitoring wells PZ260 and PZ262 as shown on Figure 4.7.

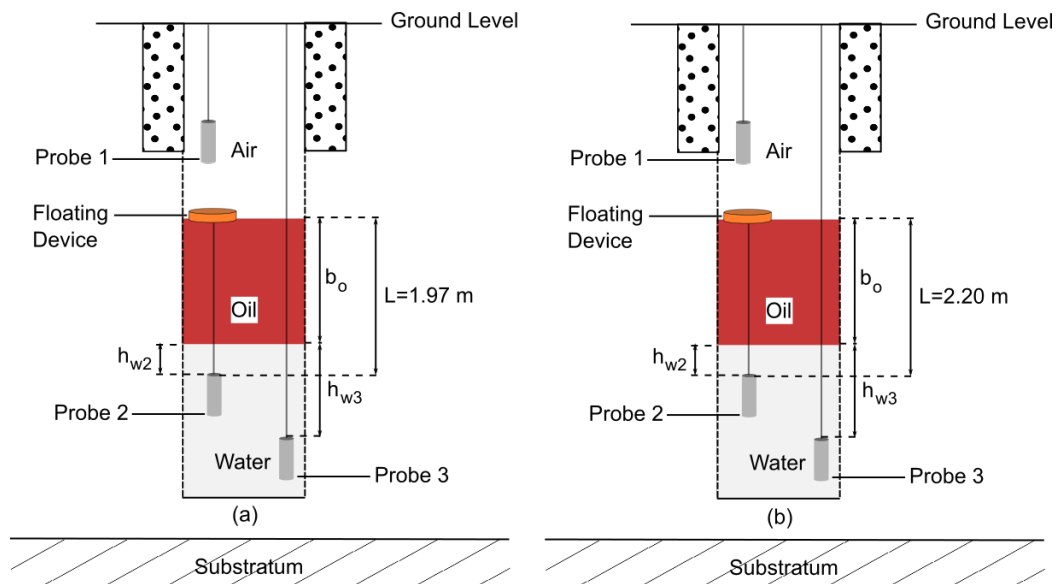


Figure 4.7: Schematic view of the automatic pressure probes installation in (a) monitoring well PZ262 and (b) monitoring well PZ260

The pressures were recorded in the well PZ260 from October 2013 to February 2014, and in the well PZ262 from September 2014 to April 2015. The data recorded by the automatic pressures probes were interpreted using Equations 2.47, 2.48, and 2.49 in order to determine the interfaces level and the oil thickness in the monitoring well.

From the manual and automatic measurements, the $\Delta b_o = f(\Delta z_{ow})$ relationship, proposed by Kemblowski and Chiang (1990), has been determined for each well, and the influence of the soil nature on this relationship in the area where the oil is present has been assessed.

4.3 Results

4.3.1 Impact of Groundwater Fluctuation on Oil Thickness in Monitoring Well

Manual Groundwater Table Measurement

The total potentiometric surface variations have been plotted for the eleven monitoring wells and compared to the groundwater fluctuation observed on a daily basis in a well outside the building without oil (PZ72). Figure 4.8 represents the total potentiometric level in all the wells, including the monitoring well PZ72.

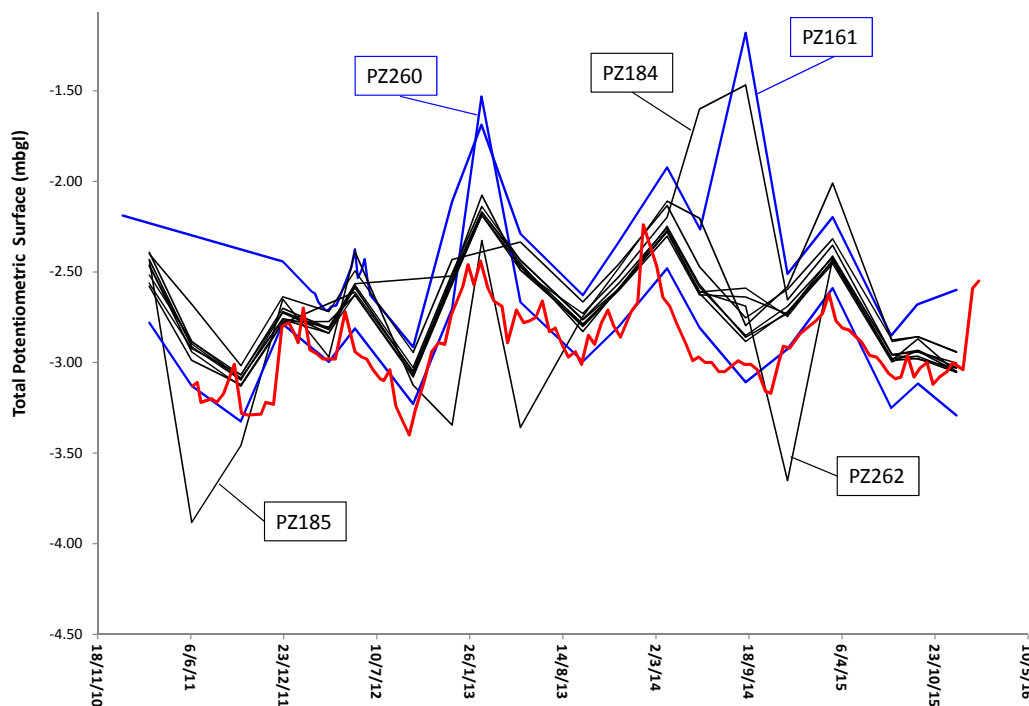


Figure 4.8: Total potentiometric surfaces fluctuation in several wells showing free oil phase (black and blue curves) and groundwater fluctuation outside the building measured on PZ72 (red curve)

The blue curves represent the wells outside the building and the black curves the wells beneath the factory building. It appears that the total potentiometric surface in wells exhibit-

ing significant oil thickness follows the general trend of the groundwater fluctuation, while average value may be different from the well PZ72 due to the piezometric gradient across the site. However, in some wells (e.g.: PZ161, PZ184, PZ260 and PZ262) the total potentiometric curve does not consistently follows the fluctuation of the groundwater table. This specific behaviour exists regardless the location of the well, inside or outside the building. It appears that the extensive cover on the ground surface with buildings and hardstanding areas does not impact the groundwater fluctuation. Therefore, the impact of the groundwater fluctuation on the oil thickness measured in the wells can be studied on the same way all across the studied site, regardless the significant impermeable surface.

Figure 4.9 shows that the wells in which the total potentiometric surface follows a different trend than the groundwater level fluctuation (greater variation than the groundwater variation or opposite variation to the groundwater fluctuation) are mainly from the wells category 2. The total potentiometric surface in the wells from category 1 follows the variation of the groundwater table. The only exception is the well PZ262 in which the total potentiometric surface dropped significantly whereas the groundwater table was rising during one measurement in November 2014. Regarding the main part of the wells from category 2, the total potentiometric variations are either significantly greater than the groundwater variations (e.g.: PZ185 in June 2011 or PZ161 and PZ260 in February 2013), or the total potentiometric variations are opposite to the groundwater fluctuations (e.g.: PZ161 and PZ184 in December 2014).

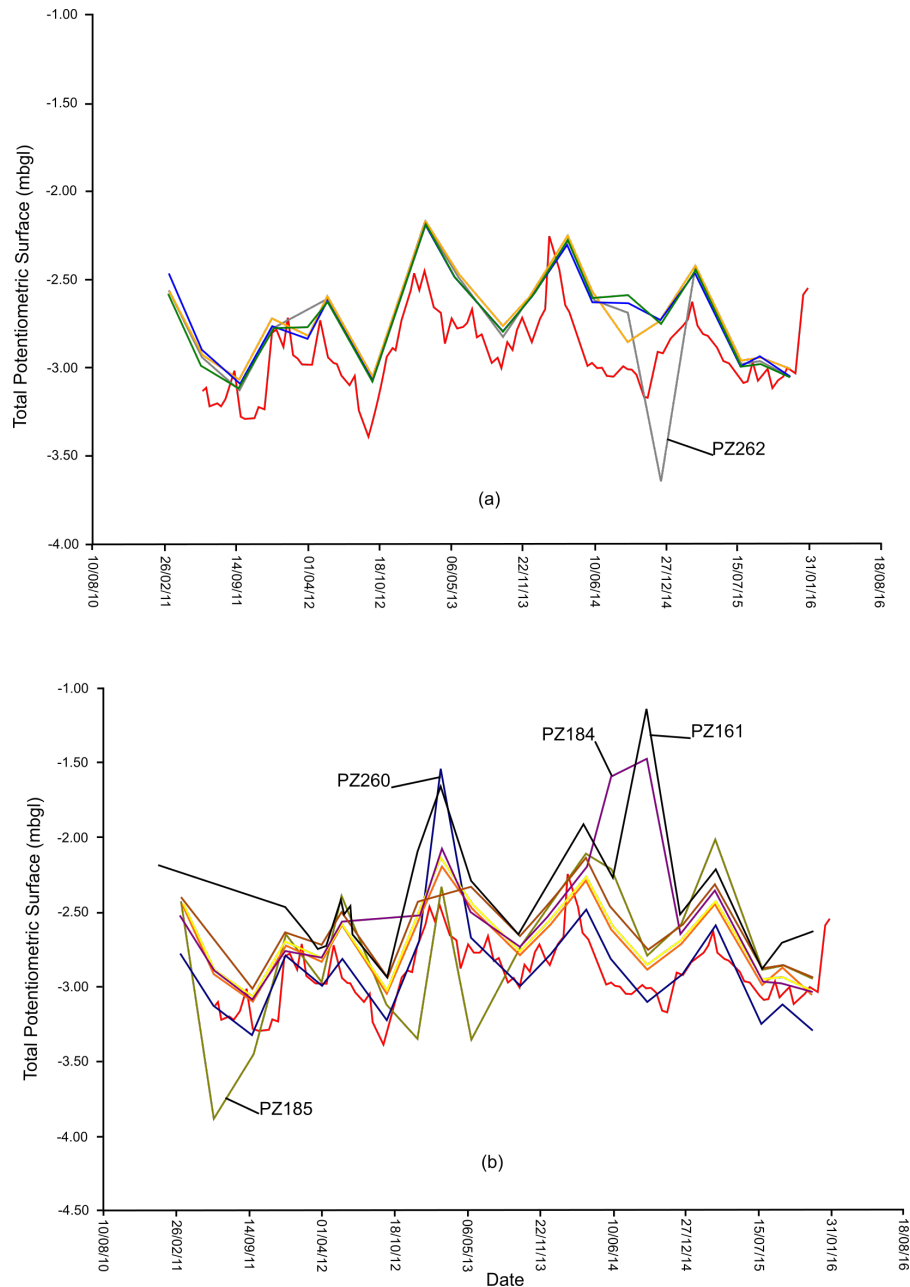


Figure 4.9: Total potentiometric surfaces fluctuation in wells from category 1 (a) and category 2 (b) along with groundwater table fluctuation (red curve)

As shown in Figure 4.10 for the monitoring well PZ264, for wells category 1, when the groundwater table drops, the oil/water interface (z_{ow}) drops as the pressure in the continuous water phase decreases, whereas the drop of the oil/air interface (z_{oa}) is in a smaller range which generates an oil thickness increase in the wells. On the contrary, when the groundwater table rises, the oil/water interface rises as the pressure in the water phase increases, and the oil thickness decreases in the monitoring wells. Thus, the oil thickness can largely vary over a short period of time; see the example in well PZ257 from 1.90 m to 0.20 m in three

months between September and December 2012. In extreme conditions, when the groundwater table is very high, the oil thickness can completely disappear from the well (e.g.: PZ262 and PZ264 in February 2013). Graphs showing the fluctuations of each interface level along with the variation of the oil thickness measured in the monitoring wells of the category 1 are presented in Annex D.

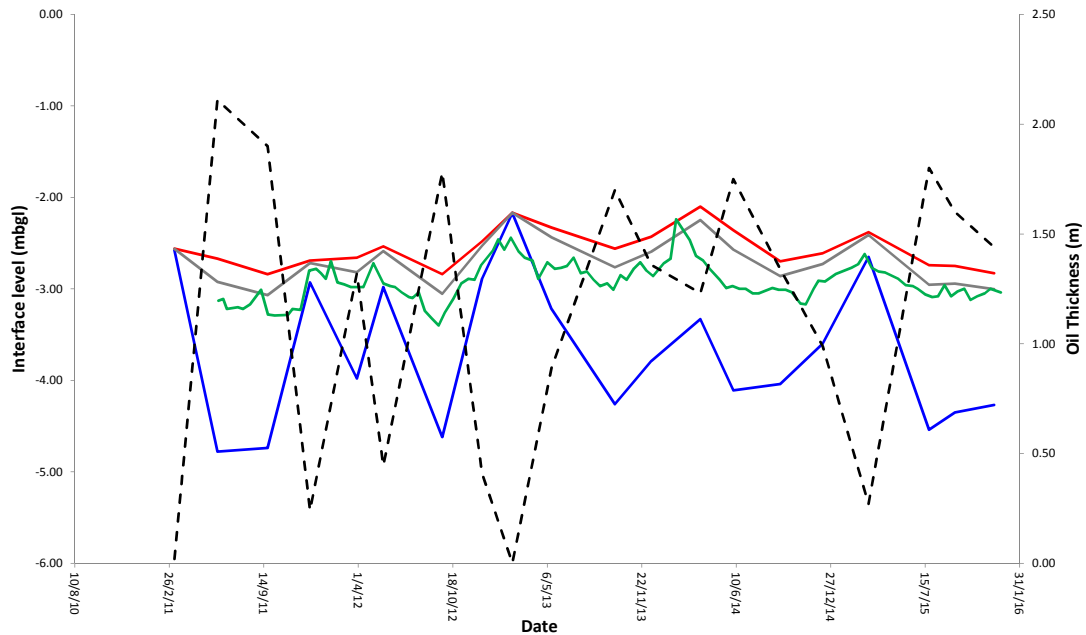


Figure 4.10: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve), groundwater table (green curve) and oil thickness (black dotted line curve) in the monitoring well PZ264

As illustrated in Figure 4.11 by the example of the well PZ264, for all the monitoring wells of the category 1, the relationship between the oil/water interface elevation change and the measured oil thickness shows a linear correlation with a negative slope confirming that the oil thickness decreases when z_{ow} increases and vice versa. The relation follows the general form $\Delta b_o = -a\Delta z_{ow} + b$, where a is the slope of the curve. For all the wells, the squared coefficient values for this relation are greater than 0.85 and the slopes vary between 0.59 and 0.82. Graphs showing the relationship between the oil/water interface elevation change and the measured oil thickness in the monitoring wells of the category 1 are presented in Annex E.

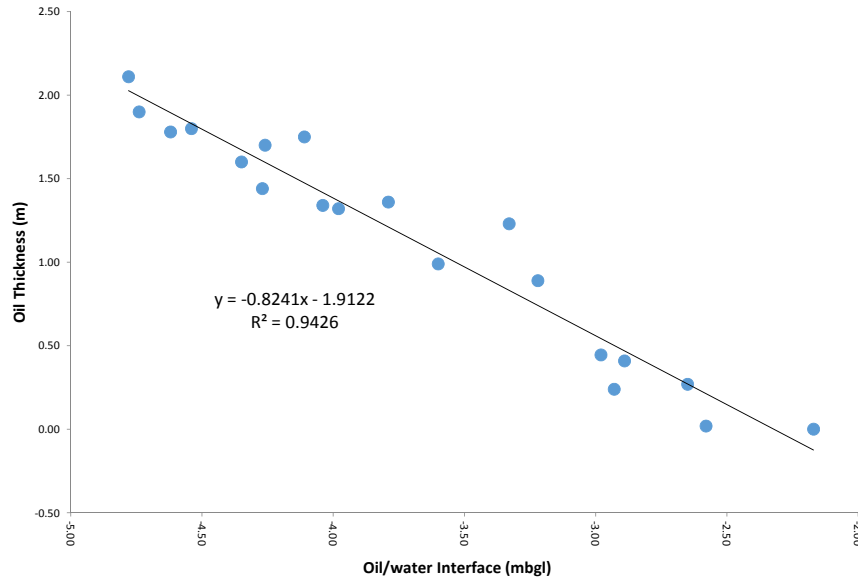


Figure 4.11: Oil/water interface level versus measured oil thickness in the monitoring well PZ264

For the wells of the category 2, two sub-categories of wells can be distinguished based on the different behaviours of the interface variations observed when groundwater table fluctuates. The first sub-category (category 2a) groups the monitoring wells PZ259 and PZ161 which closely behave similar to the wells of category 1.

- In the PZ259 the oil thickness variation presents exactly the same behaviour as the wells from category 1 when groundwater fluctuates. Considering the lithology of this well presented in Figure 4.6, it seems that the 0.20 m of silty sand layer does not play a role on the general oil mobility during groundwater table fluctuation.
- In the PZ161, the oil thickness variation presents two different behaviour when groundwater fluctuates. In the period from October 2012 to June 2014 (period II on Figure 4.12) the oil thickness variation presents exactly the same behaviour as the wells from category 1. On the other hand, from December 2011 to October 2012 and from June 2014 to December 2015 (period I and III on Figure 4.12), when the groundwater table rises, it causes a greater increase of the oil/air interface than the oil/water interface, which generates an increase in the oil thickness in the monitoring well (and vice-versa). It seems that the oil thickness variations are similar when compared to the wells in category 1 when the groundwater table fluctuations are significant, and that the oil thickness behaviour changes when the amplitude of groundwater fluctuations is lower. The formation around the well PZ161 is mainly coarse to fine sand without silty layers.

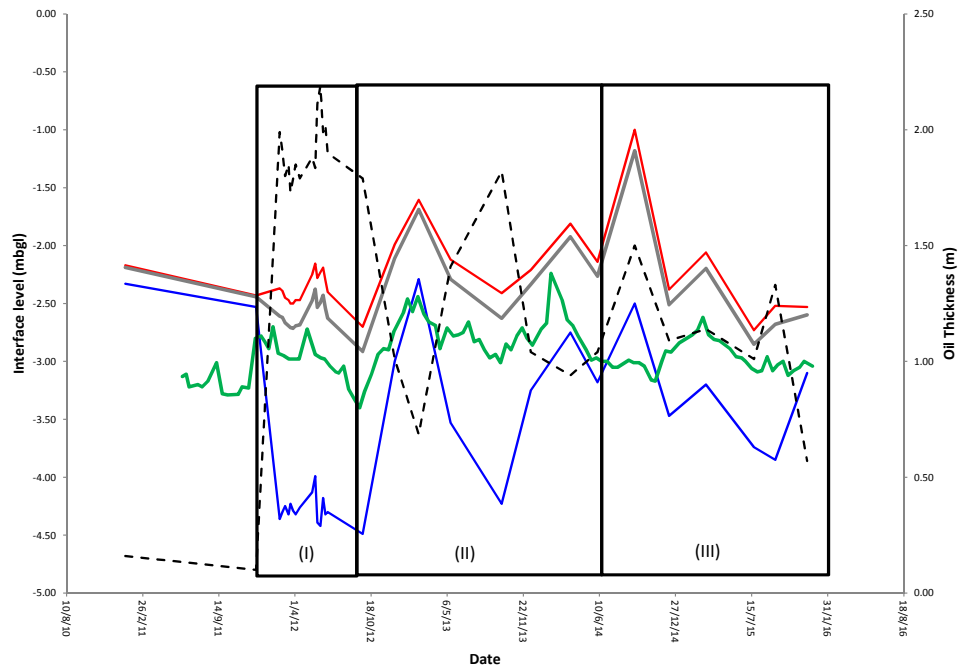


Figure 4.12: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve), groundwater table (green curve) and oil thickness (black dotted line curve) in the monitoring well PZ161

The second sub-category (2b) groups the other wells of the category 2 (PZ184, PZ185, PZ258, PZ260 and PZ261). Most of the time for all these wells, when the groundwater table rises, it causes a greater increase of the oil/air interface than the oil/water interface, which generates an increase of the oil thickness in the monitoring wells (and vice-versa). However, as observed for the well PZ161, for significant groundwater table fluctuation, when the groundwater table rises significantly on a relatively short period of time, the interfaces variations follow behaviour described for the wells category 1, and the oil thickness decreases in the monitoring wells. A clear difference between these wells and the PZ161 is that this situation is rarely encountered, only one time over the period of observation (November 2013 for the PZ258, PZ260 and PZ261 and December 2011 for the PZ184 and 185). Figure 4.13 shows the example of the monitoring well PZ260. Graphs showing the fluctuations of each interface level along with the variation of the oil thickness measured in the monitoring wells of the category 2 are presented Annex F.

For the monitoring wells of the category 2a, the relationship between the oil/water interface elevation change and the measured oil thickness exists and show a linear correlation with a negative slope confirming that the oil thickness decreases when z_{ow} increases and vice versa. The relation follows the general form $\Delta b_o = -a\Delta z_{ow} + b$.

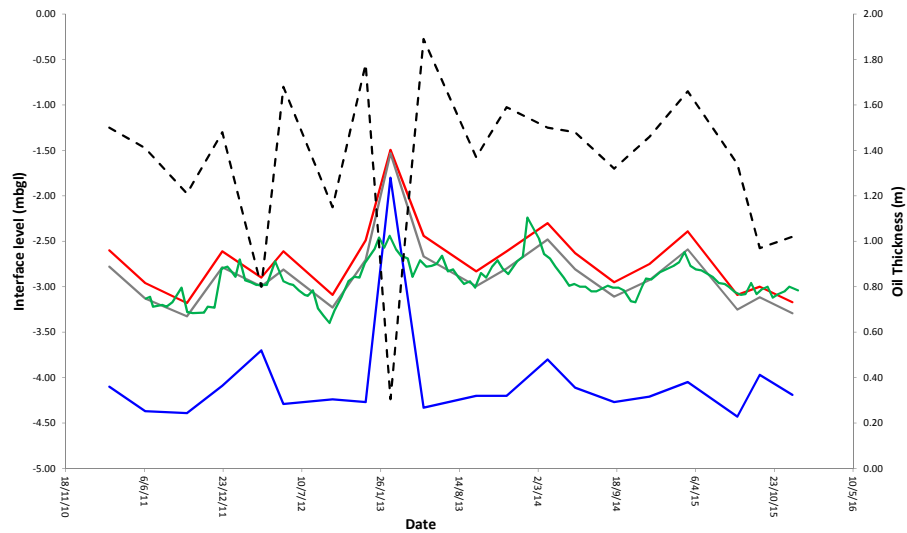


Figure 4.13: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve), groundwater table (green curve) and oil thickness (black dotted line curve) in the monitoring well PZ260

However, while the squared coefficient value for the relation of the well PZ259 reflects a good correlation (0.86), for the well PZ161 the squared coefficient is lower (0.78) reflecting data more scattered as shown in Figure 4.14.

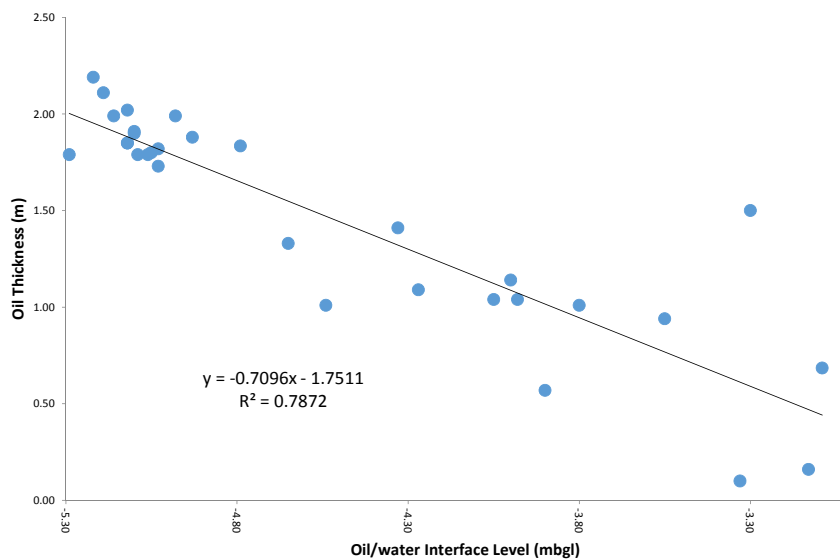


Figure 4.14: Oil/water interface level versus measured oil thickness in the monitoring well PZ161

For the monitoring wells of the category 2b, as shown Figure 4.15 for the well PZ258, the relationship between the oil/water interface elevation change and the measured oil thickness does not exist reflecting the fact that groundwater fluctuation caused different oil behaviour in the monitoring wells of this category. Graphs showing the relationship between the oil/water interface elevation change and the measured oil thickness in the monitoring wells of the category 2 are presented in Annex G.

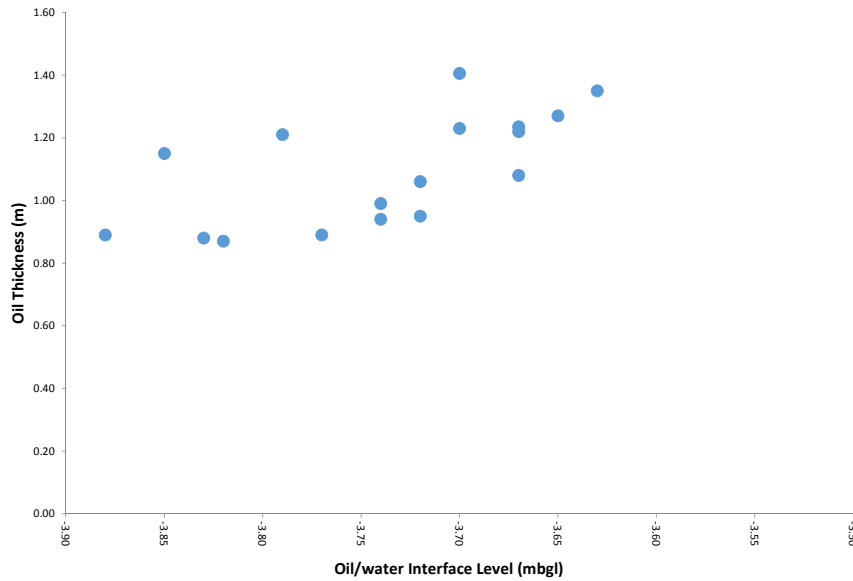


Figure 4.15: Oil/water interface level versus measured oil thickness in the monitoring well PZ258

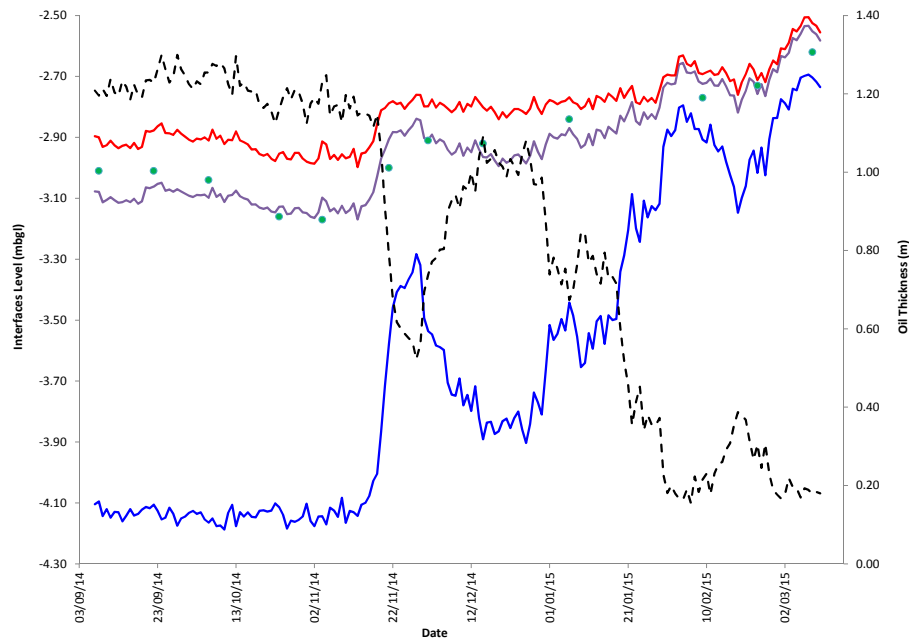
Table 4.2 summarizes the grain size distribution encountered in the formation around the well where oil is present and presents the key observations made for each well category.

Table 4.2: Monitoring wells classification based on the grain size distribution of the adjacent formation

Wells Categories	Grain-size distribution	Interfaces variations	Oil Thickness variations	Relation $\Delta b_o = -\Delta z_{ow}$
Category 1	Coarse-grained soil (gravel to coarse sand)	<ul style="list-style-type: none"> - z_{ow} fluctuates significantly - z_{oa} fluctuates slightly - z_{ow} and z_{oa} rises when groundwater table rises (and vice versa) 	<ul style="list-style-type: none"> - Oil thickness increases when groundwater table drops - Oil Thickness decreases when groundwater table rises 	<ul style="list-style-type: none"> - Linear relation with good correlation ($R^2 > 0.85$) - Different slope from 0.59 and 0.82
Category 2a	Fine-grained soil (fine sand)	<p>Two types of variation:</p> <ul style="list-style-type: none"> 1) Same than category 1 2) - z_{ow} fluctuates slightly - z_{oa} fluctuates significantly - z_{ow} and z_{oa} rises when groundwater table rises (and vice versa) 1) and 2) are equally encountered 	<ul style="list-style-type: none"> - Oil thickness is stable or increases when groundwater table rises - Oil Thickness is stable or decreases when groundwater table drops 	<ul style="list-style-type: none"> - Linear relation with fair correlation ($R^2 = 0.70$)
Category 2b	Very fine-grained soil (fine sand)	<p>Two types of variation:</p> <ul style="list-style-type: none"> 1) Same than category 1 2) - z_{ow} fluctuates slightly - z_{oa} fluctuates significantly - z_{ow} and z_{oa} rises when groundwater table rises (and vice versa) 1) is rarely encountered when groundwater rises significantly 2) is the main variation observed 	<ul style="list-style-type: none"> - Oil thickness increases when groundwater table rises - Oil Thickness decreases when groundwater table drops 	<p>The relation does not exit</p>

Automatic Groundwater Table Measurement

By acquiring data every day from the monitoring well PZ262 and every two hours from the monitoring well PZ260, the automatic pressure probes allowed further assessment of the impact of short-term groundwater fluctuations on the oil/water and oil/air interfaces movement and on the oil thickness in the monitoring wells. Figure 4.16 presents the groundwater table fluctuation along with the interfaces and oil thickness variations in the monitoring well PZ262.



262.pdf

Figure 4.16: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve), groundwater table measured manually on well PZ72 (green dots) and oil thickness (black dotted line curve) in the well PZ262 measured using automatic probes system

The interface movements and the oil thickness variations measured in the monitoring wells using the automatic pressure probes present the same characteristics as what was observed from the long-term manual measurement in the wells of the category 1. That is confirmed by the relationship between the oil/water interface elevation change and the measured oil thickness which follows the general form $\Delta b_o = -a\Delta z_{ow} + b$, as shown on Figure 4.17.

One can mention that the squared coefficient values for this relation is greater for the automatic measurement (0.99) than for the long-term manual measurement (0.85), and the slopes vary between 0.78 for the automatic measurement and 0.65 for the manual acquisition. Figure 4.16 shows that the groundwater table fluctuation from beginning of September to mid-November 2014 is fairly stable with a very low decrease of the total potentiometric surface by 0.15 m. Over this period, the interface and the oil thickness seems also fairly stable.

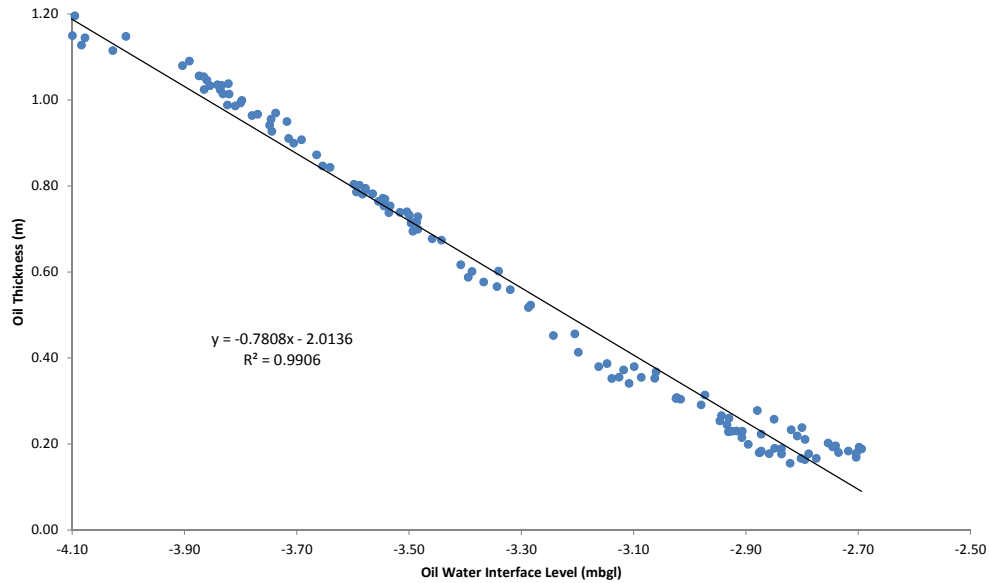
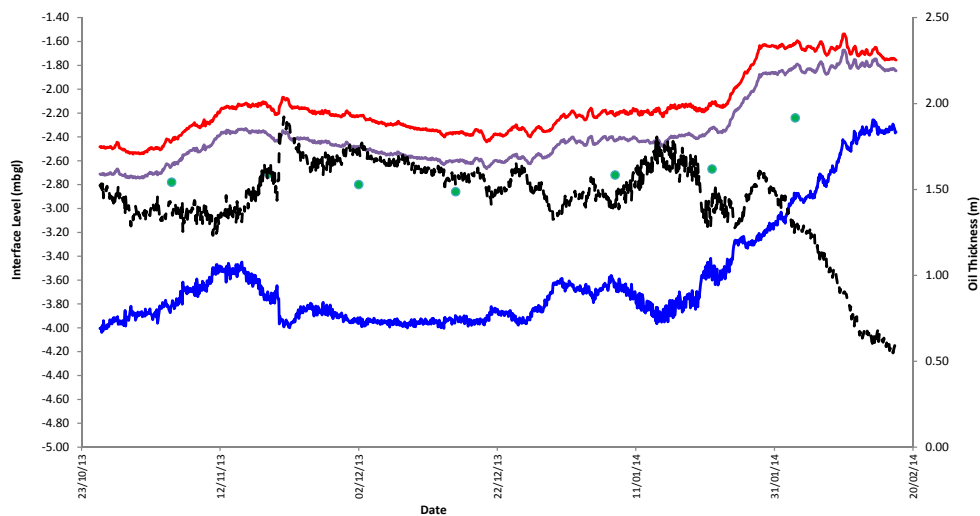


Figure 4.17: Oil/water interface level versus measured oil thickness in the monitoring well PZ262

Figure 4.18 presents the groundwater table fluctuation along with the interfaces and oil thickness variations in the monitoring well PZ260 from October to February 2014.



260.pdf

Figure 4.18: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve) and oil thickness (black dotted line curve) in the well PZ260 measured using automatic probes

This period is characterized by a constant and slow increase of the groundwater table

which is typical over the fall and winter periods. When observing short-term variations of the groundwater table, the interfaces movement and the impact on the oil thickness in the monitoring well does not consistently follow the observations made for well category 2(b), using the long-term manual measurements. Here, the behavior is more a combination of observations made for well categories 1 and 2(b), which is confirmed by the $\Delta b_o = f(\Delta z_{ow})$ curve on Figure 4.19. There is no clear single correlation curve, however during several periods, oil thickness in the monitoring well and the oil/water interface level are correlated.

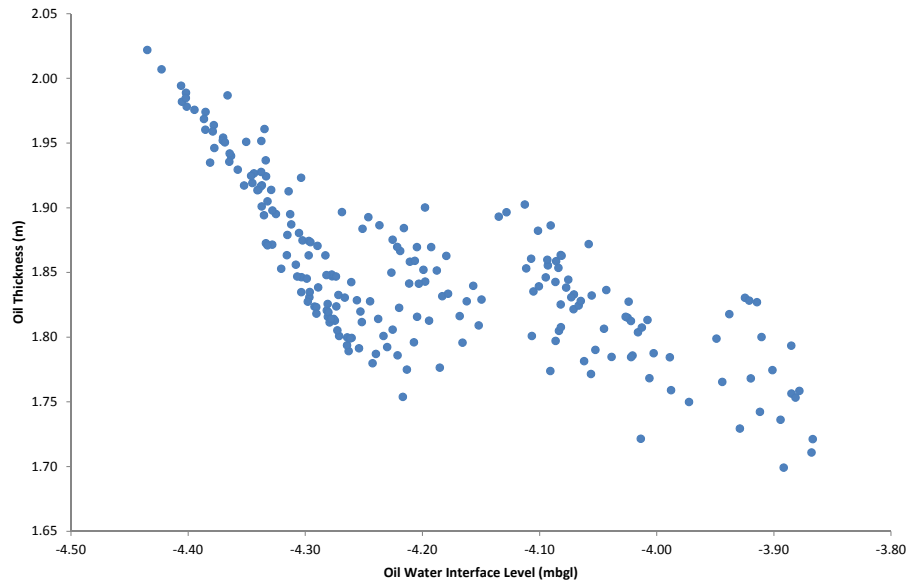


Figure 4.19: Oil/water interface level versus measured oil thickness in the monitoring well PZ260 using interfaces levels measured by automatic probes

4.3.2 Model Application to Field Observations

Unconfined Oil Layer

Automatic Data Acquisition

The solutions were first tested on the unconfined oil layer with the results of automatic data acquisition on monitoring well PZ262. Input parameters are presented in Table 4.3 .

The given approach led to a good fit of the z_{oa} value but the fit of z_{ow} was less (Figure 4.20). It appears that a small variation of z_p leads to a significant variation of z_{ow} , due to density effects. On Figure 4.20(a), the value of N_{oa} from the model, the top of the oil layer in the formation, is also shown. It can be seen that before day 70, which corresponds to the period of stable z_p (from September to mid-November 2014), N_{oa} is quite stable, and close to the level of oil/interface in the well (z_{oa}). Then a rapid rise of the groundwater table occurs.

Table 4.3: Input parameters for the solution with constant oil saturation $S_{[o]max}$

	Input Parameter Value
K_o	0.05 m/day
K_a	0.03 m/day
$N_{ow}(t_0)$	1.4 m
$N_{oa}(t_0)$	3.15 m
B_o	1.75 m
ρ_r	0.88
S_{or}	0.15
$S_{o(max)}$	0.6
h_c	0.05 m

During this period both z_{ow} and z_{oa} rise with a greater upward movement of z_{ow} . For the same period, the oil in the formation is slowly moving up. We are in case (b) of Figure 4.2, the oil level being higher in the well than the top of the oil layer in the aquifer. There is an oil flux from the well to the aquifer which explains the greater impact of the groundwater table variation on z_{ow} than on z_{oa} . Around day 85, the process reverses: the groundwater level has decreased, and thus the oil level in the well starts to be lower than the oil level in the aquifer.

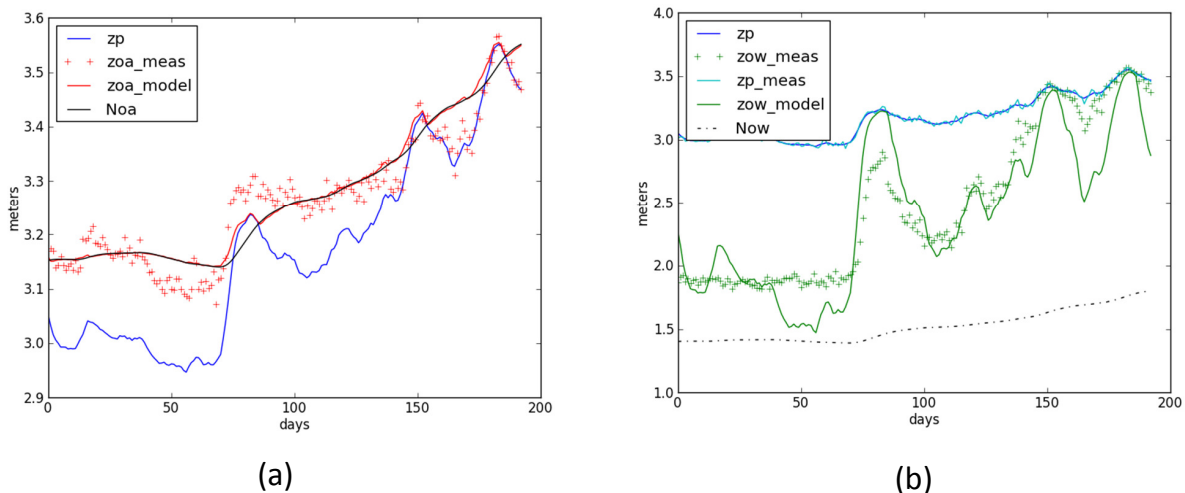


Figure 4.20: Evolution of measured (symbols) and modeled (lines) levels of the oil/air interface (a) and of the oil/water interface (b) for the case of constant saturation values, in the well PZ262 and in the formation. Model results show the best fit in the χ^2 sense

After day 150, the measured values show that both z_{oa} and z_{ow} are equal to z_p . This

means that there is no more oil in the well. At this stage it is clear that the groundwater level is higher than the oil in the formation. These types of periods can be used to fit the model, although here the top of the model did not reach this value.

The fitting process also helped us to understand some of the system behaviors. It appears that the thickness of the oil in the aquifer and its position have an effect mainly during the period when the groundwater level is stable. During other periods, the main factors influencing the thickness of the oil in the well are the transient transfers between the well and the formation. Therefore the thickness of the oil in the formation is quite difficult to estimate and requires a long period without groundwater level variations. In Equation 4.5, K_a , the hydraulic oil conductivity of the unsaturated zone was introduced. However the differences between N_{oa} and z_{oa} were often too small for this value to play a significant role and thus the results are quite insensitive to the hydraulic oil conductivity in the unsaturated zone. The results obtained with constant maximum and residual saturation showed some discrepancies in the modeled values of z_{ow} . In Figure 4.20, the slope of z_{oa} and z_{ow} rise between day 110 and 140 is almost correct suggesting that the rise of N_{ao} , and thus the estimated oil conductivity of the medium is correct. There are some differences at the beginning of the period, which could be due to previous history of the fluctuations which are not known precisely. There are also some differences at the end of the period, where z_{oa} is too high and thus z_{ow} too low. This could be due to higher saturation available for mobile oil in this medium. Several tests were done with the same input parameters and using higher maximum saturation values in the top layers (each layer having 10 cm thickness), and then optimize the model for the values of hydraulic conductivity. Figure 4.21 shows that the fit for variable saturation values is much better than the fit for constant saturation values (Figure 4.20), mainly from day 140 to the end, where almost no discrepancy remains.

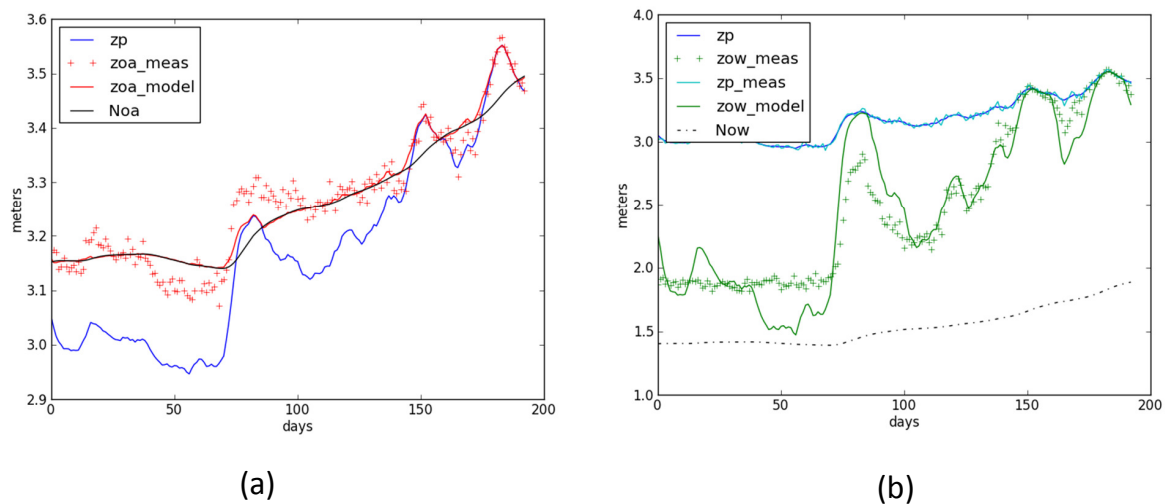


Figure 4.21: Evolution of measured (symbols) and modeled (lines) levels of the oil/air interface (a) and of the oil/water interface (b) for the case of variable saturation values, in the well PZ262 and in the formation. Model results show the best fit in the χ^2 sense

The fit for the previous periods is not better than in the constant saturation model. The fitted oil conductivity is equal to 0.05 m/day (3.5×10^{-5} m²/min) which is the range of plausible values for this well having a high permeability. The value found by bail-down interpretation for the well PZ 262 was 0.015 m/day (1×10^{-5} m²/min) in June 2013 at t_2 .

The results were not better using a variable value for S_{or} in the air or water zone. This may be due to the fact that the medium is quite coarse and that the value of both S_{orv} and S_{ors} may be small.

Long-term Manual Acquisition

On the wells with long term manual measurements, we applied the same modeling approach. The piezometric head data are provided every ten days at the reference point (monitoring well PZ72) while the oil levels were measured every two or three months. It can be seen that for this well the fit is also good. However the sensitivity to the input parameters is small and thus the uncertainty in the parameter's value is high. This has two main reasons: the manual measurements are of less quality than the automatic measurements, and there is no series of data on a short time scale to fit correctly the oil conductivity. Again the true thickness of the oil in the aquifer is difficult to determine with this approach. On this example, it was not possible to assess the potential vertical variations of saturation. Despite these uncertainties, the fitted oil conductivity, 0.07 m/day is quite close to the one of the previous well and is in a range of plausible values.

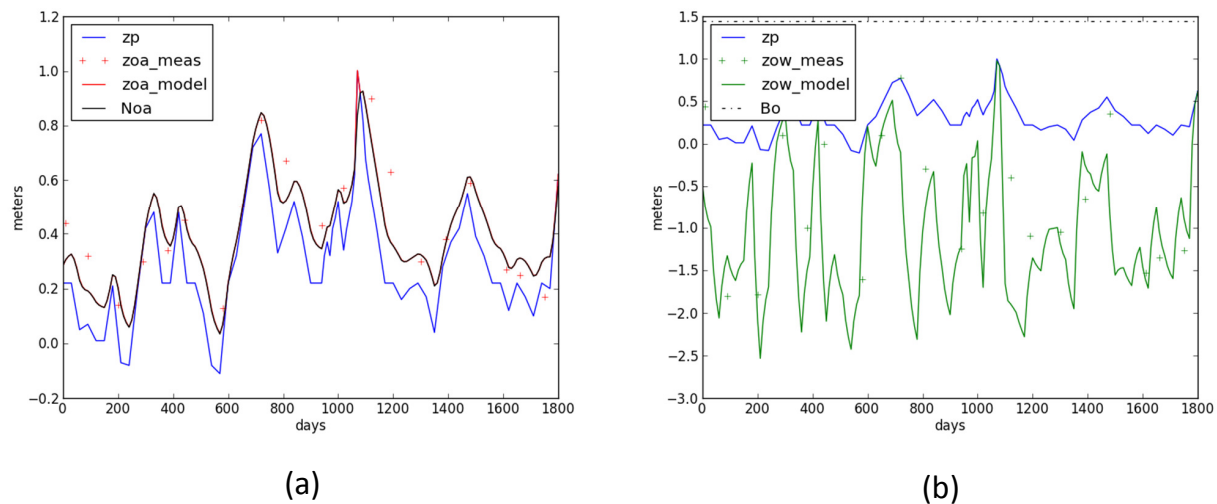


Figure 4.22: Evolution of measured (symbols) and modeled (lines) levels of the oil/air interface (a) and of the oil/water interface (b) in the well PZ264 and in the formation. Model results show the best fit in the χ^2 sense

Confined Oil Layer

Automatic measurements

In this area some layers of silt were identified, it is therefore possible that the oil movement in

this well might be semi-confined or confined. The confined model was thus applied through the use of variable oil permeability with depth. The input parameters are presented in Table 4.4.

Table 4.4: Input parameters for the solution with constant oil saturation $S_{[o]max}$

	Input Parameter Value
K_o	Variable
K_a	0.03 m/day
$N_{ow}(t_0)$	2.3 m
$N_{oa}(t_0)$	4.2 m
B_o	1.9 m
ρ_r	0.85
S_{or}	0.15
$S_{o(max)}$	0.6
h_c	0.1 m

The model gave a good fit for z_{oa} and only some limited discrepancies for z_{ow} (Figure 4.23). This behavior was difficult to model for several reasons. In unconfined situations the level of the oil in the aquifer (N_{oa}) followed with some delay the level of the oil/air interface in the well (z_{oa}). Applying this approach gave a completely wrong evolution of z_{ow} . This led us to suppose the presence of a layer of very low K_o . This also leads to a quasi immobile oil layer. However some rapid variations of z_{ow} occurred before 20 days and after 90 days.

These variations seem to be due to the presence of layers of average K_o below the silt layer and one of high K_o on top of it. It is of particular interest to look at the rapid variation after day 90. z_{oa} rises almost at the same velocity as z_p , but when z_p becomes stable z_{oa} decreases, which suggests that N_{oa} is lower. Between days 90 and 115, z_p is stable but z_{oa} is still decreasing, suggesting that N_{oa} remains lower than z_{ao} over the entire period. Thus, there is a low K_{ov} value for the oil. When reaching a z between 4.2 and 4.4, K_{oh} is significant as the oil in the well can move to the formation, which is also reflected by the significant increase (2m) of z_{ow} .

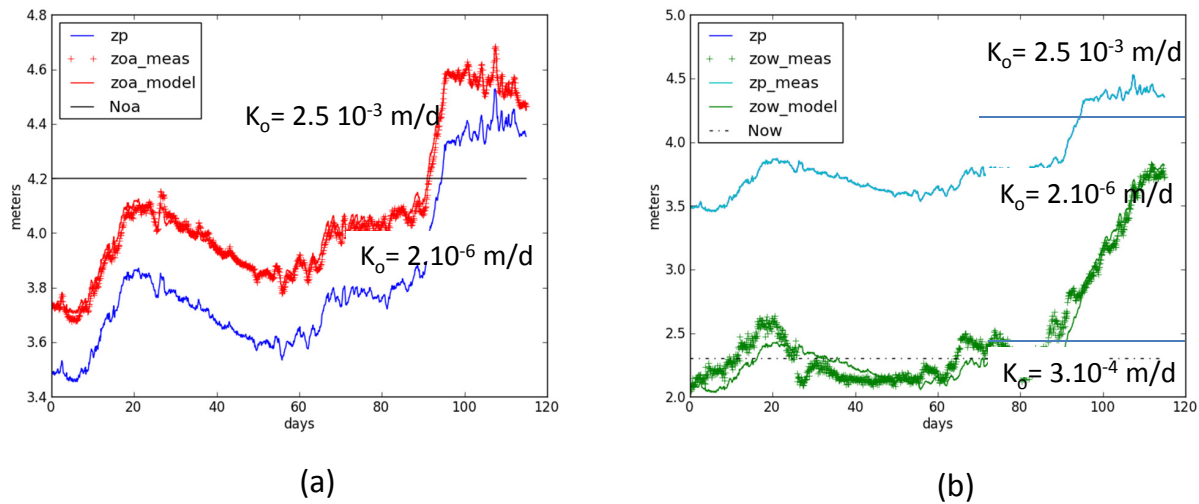


Figure 4.23: Evolution of the measured (symbols) and modeled (straight line) levels of the oil/air interface (a) and of the oil/water interface (b), in the well PZ260 and in the formation. On (b) the values of the fitted hydraulic oil conductivities are given for the three identified layers

Long-term manual acquisition

As for unconfined medium, the estimated parameters on long term series are much more uncertain than for automatic measurements.

Overall, the behavior of the oil in the well in confined medium can be quite complex. In general it was seen that the oil thickness in the well remains constant when this oil is in front of a silt layer. If a higher K_o layer is present below this one, there will be variations comparable to unconfined ones when z_{ow} is low. On the contrary, with a high K_o layer on top of the silt the variations will be significant when z_{oa} becomes high.

4.4 Discussion and Conclusions

This study gives a detailed description of groundwater table variation impact on the oil thickness in the adjacent monitoring well. Based on manual and automatic measurements of the oil thickness in monitoring wells over four years, the study confirms some elements given by others (Kemblowski and Chiang, 1990; Mayer and Hassanizadeh, 2005) providing more detailed descriptions of the interfaces movements for both unconfined and confined conditions. These results are based on manual and automatic measurement of the oil thickness in monitoring wells over four years.

As mentioned by several authors, in particular Huntley *et al.* (1992) and, Marinelli and Durnford (1996)), this study confirms that the oil thickness value in monitoring wells should be used with caution. The oil thickness value at t time depends on the history of the groundwater table fluctuation and, on the total potentiometric level at the time of the measurement. For example, if the groundwater table is at a lower position than the oil layer in the adjacent formation, the equilibration process will lead to an exaggerated oil thickness

in the monitoring well. The groundwater table parameter overlaps with the soil heterogeneity which also impact the oil thickness in monitoring wells at equilibrium conditions. Thus, the oil thickness measurements for short-term decision on a remediation design is useless, and can lead to substantial error.

However, this study shows that oil thickness measurements in monitoring wells for a long-term period presents some notable observations:

- *Unconfined or Confined Oil Layer Assessment*

This study also shows that $\Delta b_o = -a\Delta z_{ow} + b$ relationship exists when the oil layer is under unconfined condition, whereas, under semi-confined or confined conditions the relationship does not exist. This confirms what has been described by Kemblowski and Chiang (1990), and it is a simple approach to screen an investigation site, determining the areas with predominantly homogeneous coarse-grained formation, and the others where more fine-grained layers are present. One can mention that, even if unconfined conditions are mainly encountered on our study site, the values of the slope are consistently different than the 0.45 reported by Kemblowski and Chiang (1990) for equilibrium conditions. This confirms that the oil is permanently under non-equilibrium conditions.

- *Oil Layer Thickness in the Soil*

Over a significant period of time, such as a year, the groundwater table varies between maximum and minimum levels which exaggerate or minimize the oil thickness measured in the monitoring well. Taking the average value of the oil thickness measured over a year may give a good indication of the oil thickness in the formation. Considering the monitoring well PZ260 for which the oil saturation has been measured at depth, the oil saturation profile (Annex C) shows that the oil layer is roughly 1.30 m thick. Table 4.5 presents the average oil thickness over four year, from 2012 to 2015, and the oil thicknesses average per year.

Table 4.5: Average Measured Oil Thicknesses in Monitoring Well PZ260 from 2012 to 2015

Year	Oil Thickness Average
2012	1.28
2013	1.34
2014	1.47
2015	1.29
Entire Period	1.34

These results confirm that the average oil thickness from measurement in monitoring wells over a significant period of time (at least a year) gives a good indication of the oil layer thickness in the adjacent formation.

Another way to estimate the oil thickness in the formation would be to consider the oil thickness in the monitoring well after a long period of fairly stable groundwater table. In that case, oil in the well and oil in the formation should have sufficient time to equilibrate. Therefore, the oil thickness in the well should represent the oil thickness in the formation as suggested by multi-phase models (Parker, 1989; Farr *et al.*, 1990)). If over a significant period (more than a month), the groundwater table is fairly stable, one can estimate the oil thickness in the formation as the system gets time to equilibrate to this value. Figure 4.24 shows oil thicknesses in monitoring wells during the fairly stable period that occurred on our studied site from beginning of September to end of November 2014.

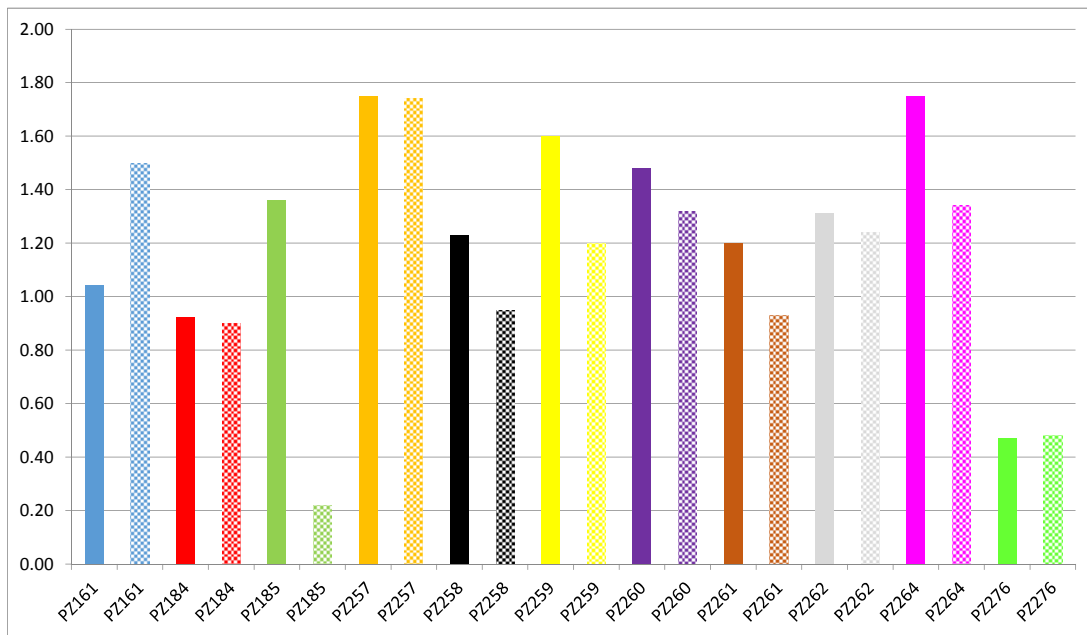


Figure 4.24: Oil thicknesses measured in monitoring wells from September to November 2014. For each well, the first value was measured at the beginning of September 2014 and the second value was measured at the end of November 2014

Considering the monitoring well PZ260, one can see that the oil thickness in the well after the equilibration period is 1.30 m which agrees well with the analytical information and with the average thickness calculated from a significant measurement period. It is important to mention that this approach must be considered carefully when used for a confined aquifer. In that case, two scenarios are possible. If the groundwater table is at the same level or above the oil layer in the formation, then the equilibration process will lead to a representative oil thickness in the monitoring well. On the contrary, if the groundwater table is lower than the oil layer position in the formation, the equilibration process will lead to an exaggerated oil thickness in the monitoring well that is not representative of the oil layer thickness in the formation.

Finally, the proposed model based on simplifying assumptions gives fairly good estimation of the oil thickness in the formation when applied to automatic data acquisition. The model works well for both unconfined and confined (semi-confined) conditions. Application to low frequency measurement is more uncertain as the low quantity of data does not allow to fit well the model. One can notice that the simplifying assumptions applied to describe the oil layer in the formation do not align with the basis of the multi-phase models. While it accounts for residual saturations, the model ignores the role of the capillary forces that lead to a varying oil vertical saturation distribution. This vertical oil saturation profile leads to a distribution of the oil relative permeability. In the developed model, K_o is considered to have a constant value over the entire oil layer. This conceptual approach does not represent the real conditions. However, the approach gives reasonable values that would be useful for estimating oil layer thickness in a formation around a monitoring well.

As estimations from each approach include uncertainties that are difficult to quantify, it would be valuable to apply the three approaches for estimating the oil layer thickness in the adjacent formation. Close results would confirm the good range of the obtained value.

- *Hydraulic Oil Conductivity*

Using Darcy's law, the proposed model also allows the estimation of the hydraulic oil conductivity of the formation, where the oil layer is present. The obtained values for the two studied wells are in a good range when considering the site-specific conditions. For the monitoring well PZ262, the estimated K_o value from the model is 0.05 m/day (3.5×10^{-5} m²/min). The data used for the PZ262 were acquired from September 2014 to March 2015. The estimated hydraulic oil conductivity value obtained at t_2 , in June 2013, from bail-down test interpretation using the modified Bouwer and Rice solution (Huntley, 2000), was 0.015 m/day (1×10^{-5} m²/min).

For the PZ260, the estimated K_o values are 0.0025 m/day (1.7×10^{-6} m²/min) and 0.00034 m/d (2.4×10^{-7} m²/min) for the most permeable layers. The data used for the PZ260 were acquired from October 2013 to February 2014. The estimated hydraulic oil conductivity obtained from bail-down test using the modified Bouwer and Rice solution (Huntley, 2000) at t_2 for PZ260 was 0.05 m/day (3.5×10^{-5} m²/min).

The estimated hydraulic oil conductivity values from the model and from the bail-down test interpretation are of the same order of magnitude for the well PZ262. For the well PZ260, it is assumed that the bail-down test gives the hydraulic oil transmissivity of the most permeable layer. If we compare the value given by the model for this layer (0.0025 m/day) to the value obtained from the bail-down test interpretation (0.05 m/day), there is an order of magnitude difference.

The proposed model seems to give good estimation of the hydraulic conductivity values for unconfined oil layer. For the confined condition, the difference between the modeled and the measured hydraulic oil conductivity requires further investigation. In particular, the complex influence of the position of the oil in the well as compared to

the confining layer and to the oil position in the formation need to be further studied to confirm the model validity.

Chapter 5

General Discussion and Conclusion

Discussion

More and more across Europe, oil removal from the subsurface is required regardless the risk that the product presents for human health and environment. This obligation generates substantial cleanup costs for site owners and governments which involve agencies for remediating when owners fail to do the removal. The associated costs depend on the extent of the contamination and on the site specific conditions. It is a key interest for the liable entity to anticipate the cost and the timing of the project, which are usually closely related. It is somewhat difficult to estimate the investigation costs, as a lot of unknowns are present before the project start (e.g.: what will be the extent of the issue, how many phases of work will be necessary to delineate the contamination, how many issues will be encountered during the drilling with subsurface infrastructure, etc.). The investigation phase is the critical step during which a maximum of information needs to be gathered concerning the oil nature, extent and behavior in the subsurface. The better the investigation, the greater the confidence will be in the cost and timing estimates for the cleanup actions. More, a good understanding of the oil behavior and mobility over the site assessment phase should allow the practitioners to i) right-size the design of the recovery network, ii) optimize the operation of the recovery systems and, therefore iii) reduce the costs of the remediation. This study provides outcomes in particular regarding the validity of the bail-down test interpretation methods, and the impact of the groundwater fluctuation on the oil mobility that should allow to improve the approach for assessing and remediating an oil contaminated site.

Scientific Outcome

The Bail-down Tests

This study shows that, in homogeneous conditions, the theoretical model proposed by Parker *et al.* (1987) to estimate the oil transmissivity from the oil thickness in a monitoring well and the interpretation of bail-down tests performed in the same well give very close oil transmissivity values. The Parker *et al.* (1987) solution gives the oil vertical distribution and quantifies the oil mobility from known i) soil and product physical properties, and ii)

oil thickness in the monitoring well at equilibrium. The study shows that when applying the Parker model for estimating the oil transmissivity in coarse-grained soil, the Burdine relative permeability model (Burdine *et al.*, 1953) gives results closer to the measured oil transmissivity than when applying the Mualem model (Mualem, 1976). This result confirms the limited information in the literature (Charbeneau, 2007) that suggest that the Burdine model gives better results for coarse-grained media and that the Mualem model gives better results for fine-grained media. However, the Parker model relies on equilibrium and homogeneous conditions. The study shows that a two-phase system requires a very long time to equilibrate, and is constantly affected by the groundwater table fluctuation which likely leads to constant non-equilibrium conditions. In addition, the field study, as in the majority of study areas, is predominantly heterogeneous. Therefore, the Parker model should be used with caution for high-level first estimates, and the bail-down test is the only field test that allows an estimation of the oil mobility around a well.

Whereas the validity of the analytical solutions for a bail-down test in a two-phase system (modified Bouwer and Rice by Huntley (2000), modified Cooper by Beckett and Lyverse (2002), and modified Jacob and Lohman by Huntley (2000) solutions) and the range of error introduced by these different approaches are still being discussed (Batu, 2012, 2013; Charbeneau *et al.*, 2013), this study confirms from laboratory simulations and from a large number of field measurements that the bail-down test is a reliable approach for assessing the oil transmissivity in the vicinity of monitoring wells. The commonly used methods of interpretation cited above, and modified Jacob and Lohman (Huntley, 2000) solutions gives valid results with differences between 20 and 30%, which is consistent with what is reported in the literature (Charbeneau, 2012). However, the test and its interpretation need to be carefully done, and the study shows that to get good results from the bail-down tests the following aspects have to be considered.

- *Measurement of the Interfaces*

The results from bail-down tests can be largely impacted by the quality of the collected data and by omitting some interpretation steps. The ASTM Standard E2856-13 and the API LNAPL Transmissivity Workbook (Charbeneau, 2012) recommend that following the baildown stage of oil removal, the interfaces are manually measured using interface probes. The measurement of the interfaces level using a manual interface probe is straightforward when a distinct separation exists between the phases (i.e.: the probe goes suddenly from water to pure oil). In fact, the study shows that in some circumstances, the manual measurement of the interfaces may introduce errors that lead to non-interpretable data sets. The measurement errors occur most of the time on the oil/water interface level. The main assumption is that the measurement errors are caused by the presence of emulsified oil phase between the oil and the water, and bacteria that play a role in oil degradation. As the interface probe measures the conductivity of an electrical signal between two electrodes, this distinguishes whether the probe is in the water (high electrical conductivity) or in the oil (low electrical conductivity). Therefore, the presence of emulsion or bacteria can easily result in a misinterpretation of the signal from the interface probes. During this study, the presence of bacteria and emulsion has been confirmed by taking undisturbed samples

of the liquid column using a transparent plastic bailer. These measurement errors on the oil/air interface level leads to uninterpretable data. To circumvent this issue, we proposed to calculate the oil drawdown considering the oil/air and the oil/water interfaces ($s'_{o(t)}$). This approach allowed interpreting more data sets, but for this points the interpretation methods give different results. Therefore, the preferable approach is to use automated data acquisition. This solution has been successfully tested using three pressure probes and following the protocol described in the Section 2.2.1. This method requires the practitioner to carefully measure the length L between the floating device and the probe 2 (see Figure 2.11) as this parameter is critical to determine all the interfaces levels. Another way to automatically measure the interfaces would be to use an acoustic range finder and a transducer as proposed by Hampton (2003). The other benefit when using automatic data acquisition is that it allows the practitioners to perform several bail-down tests at the same time, whereas the manual measurement allows a maximum of two to three bail-down tests to be performed at the same time. This is a key interest as the study shows that the groundwater fluctuation largely impacts the oil thickness in the monitoring wells and the oil transmissivity. Therefore, performing bail-down tests to assess the oil transmissivity on a site and identifying the most transmissive areas requires the tests be performed during the same period.

- *Relationship Between the Oil Drawdown and the Oil Thickness into the Well (J_{Ratio})*
The relationship between the oil drawdown and the oil thickness into the well, called J_{Ratio} , is a valuable analysis to confirm that the data set is suitable for the modified Bouwer and Rice solutions (Lundy and Zimmerman, 1996; Huntley, 2000) as suggested by Kirkman (2013). In addition, this study shows that the J_{Ratio} may also be an interesting tool to assess whether the data set quality is good enough to be interpreted. In fact and as mentioned above, the manual data acquisition may introduce measurement errors depending on the site conditions. Moreover, the J_{Ratio} squared coefficient approaches 1 and the J_{Ratio} value reaches $-(1 - \rho)$, more data sets could be interpreted (regardless the interpretation method). A good relationship between the oil drawdown and the oil thickness in the monitoring well will ensure a clear oil drawdown curve without scattered data that make the graphical interpretation questionable. The J_{Ratio} is therefore a good tool to assess the quality of the collected datasets.
- *Relationship Between the Oil Discharge into the Well and the Oil Drawdown*
The relationship between the oil discharge into the well and the oil drawdown is a key diagnostic tool to understand if the oil in the well was in equilibrium with the oil in the adjacent formation (Charbeneau, 2012). From this analysis, a correction of the initial oil drawdown may be required before interpreting the data. The analysis of this relationship is interesting as it showed that even at the laboratory scale, the equilibrium conditions between the wells and the adjacent media are not often satisfied. This has been confirmed by the study on the groundwater fluctuation; although the total potentiometric surface is stable over a period of 5 months, during most of this time the fluids are still moving and equilibrating within the system.

- *Time-cut and Time-adjustment*

Early-time data are significantly impacted by filtering-pack recharge and by other effects as shown with the laboratory simulation of bail-down tests. Therefore, a cut-off time needs to be applied so that early data is not considered in the interpretation as suggested by several authors (Bouwer and Rice, 1976; Huntley, 2000; Charbeneau, 2012). Time-adjustment is critical for the modified Cooper (Beckett and Lyverse, 2002), and the modified Jacob and Lohman (Huntley, 2000) solutions as these methods include a oil storage coefficient, which is a capacitance factor, and time origin is significant to the theoretical model (Charbeneau, 2012). Applying the relationship between the time cut-off and the time adjustment suggested by Charbeneau (2012) gives reasonable results as confirmed by the good correlation between the transmissivity values obtained from the three interpretation methods.

- *Storage Coefficient*

Some methods require an estimate of the storage coefficient, e.g.: modified Cooper (Beckett and Lyverse, 2002), and modified Jacob and Lohman (Huntley, 2000) solutions. When applying those methods, the study confirms that for an unconfined aquifer, a reasonable porosity value can be used as starting point as suggested by Charbeneau (2012). When all the above corrections are applied, the obtained S shall be in the range of possible values.

Assumptions to explain the validity of the bail-down test

The key assumptions did not seem to be verified from a 'first look'. But, as shown in Tables 5.1 and 5.2, a detailed analysis suggests that due to high oil viscosity, the conditions are close to be verified in the aquifer. More than the oil viscosity itself, the fact that the bail-down test is working is probably linked to the velocity of the oil in the porous media. If the oil flow is slow enough then the key assumptions of the analytical solutions are verified. Therefore, the validity of the bail-down test is dependent on parameters that lead to hydraulic oil conductivity. Referering to Equation 2.12, these parameters are essentially the viscosity, which is an internal resistance opposing the fluid flow, the fluid density, and the intrinsic soil permeability. The results of this study are therefore valid for the tested conditions, but may not work if a lighter contaminant such as diesel had been the pollutant.

Table 5.1: Common assumptions of the three interpretation methods (modified Bouwer and Rice, modified Cooper *et al.*, and modified Jacob and Lohman), along with specific assumptions of the modified Bouwer and Rice solutions for interpreting the bail-down tests in dual-phase systems

Interpretation Approaches	Key Assumptions	How the assumption is verified during a bail-down test
Common assumptions to all interpretation methods	Free oil layer has infinite areal extent	i) The well diameter is very small compared to the oil horizontal extent, and ii) due to its relative high viscosity, the oil volume that can flow to the well is not limited over the test period.
	Aquifer is homogeneous and has uniform thickness	i) As shown on the borehole logs (Figure 4.6), the aquifer thickness where oil is present is usually fairly homogeneous, and ii) the radius of influence of the test is small enough to consider that no heterogeneity disturbs the horizontal flow of the oil to the well.
	Oil potentiometric surface is initially horizontal	Before the test, the oil phase is immobile, there is no gradient in the oil phase.
	The oil recovery to initiate the test is instantaneous	Condition of the test that the practitioner should apply.
Modified Bouwer and Rice Solutions Lundy and Zimmerman (1996) Huntley (2000) Kirkman (2013)	(b.1) Oil return flow is quasi-steady-state	As oil viscosity slows down the return flow of oil to the well, it can be considered as a series of steady-state flows
	(b.2) The oil drawdown initiated by the oil removal around the well is relatively small when compared with the thickness of the oil saturated layer	Due to the oil viscosity, the initial oil drawdown in the well has a limited impact in the adjacent formation generating a very small oil drawdown which can be neglected when compared to the oil thickness in the formation.

Table 5.2: Assumptions of the modified Cooper *et al.* and of the Jacob and Lohman solutions for interpreting the bail-down test in dual-phase systems

Interpretation Approaches	Key Assumptions	How the assumption is verified during a bail-down test
Modified Cooper <i>et al.</i> Solution	(d.1 and f.1) Free oil layer is confined and has infinite areal extent	i) The well diameter is very small compared to the oil horizontal extent, ii) due to its viscosity, the oil volume that can flow to the well is not limited over the test period, and iii) the drawdown in the formation is very small which makes the oil flow horizontal verifying the assumption of confined oil layer.
Beckett and Lyverse (2002)	(d.2) Oil flow to the well is unsteady	This is the nature of the bail-down.
Modified Jacob and Lohman Solution	(f.2) Oil recovery is assumed to be slow enough to consider a pseudo-steady-state condition	As oil viscosity slows down the return flow of oil to the well, it can be considered as a series of steady-state flows
Huntley (2000)		

To further discuss and expand on the conclusion of this study, a detailed review of the conditions of the few existing studies on the bail-down test in two-phase system have been made.

- Huntley *et al.* (1992) compared the oil transmissivity obtained from bail-down tests interpreted using Jacob and Lohman (1952) to the oil transmissivity estimated with Parker *et al.* (1987) model combined with the Mualem (1976) relative permeability model. Huntley made the comparison on three wells located in fine to silty sand where diesel range product is present. He obtained a good correlation between the transmissivities, with less than 20% difference. The range of the transmissivity values obtained by Huntley goes from 1.10^{-5} to 6.10^{-5} m/min, which is low for a diesel range product. These low values are triggered by the fine-grained formation of the studied site. Therefore, when applying Jacob and Lohman (1952) method, the critical assumptions (confined oil, pseudo-steady-state return to the well) may have been satisfied by the poor conductivity range of the formation, leading to a slow recharge flow to the well that allows:
 - No limitation of the oil volume that can flow to the well over the test period.
 - A very small drawdown around the tested well.
 - A series of steady-state flows.
- Krol (1995) compared the oil transmissivity obtained from bail-down tests interpreted using Jacob and Lohman (1952) and the modified Bouwer and Rice (Lundy and Zimmerman, 1996). Krol made the comparison on three wells located in a coarse sand to gravel aquifer contaminated with petroleum distillates (product density ranges between 0.75 and 0.83). In her study the hydraulic oil conductivity values obtained using the modified Bouwer and Rice solution were consistently lower by at least one order of magnitude than the values obtained using the Jacob and Lohman solution. As shown in our study, the Lundy and Zimmerman simplifying assumption for draw-down calculation is rarely satisfied for a coarse-grained soil. Therefore, this assumption was probably not satisfied when Krol made the bail-down, introducing an error which explains the observed discrepancy.
- Kolhatkar *et al.* (2000) compared the oil transmissivity obtained from bail-down tests interpreted using modified Bouwer and Rice (Lundy and Zimmerman, 1996; Huntley, 2000), with the transmissivity estimated with Parker *et al.* (1987) model combined with the Burdine *et al.* (1953) relative permeability model. Kolhatkar made the comparison on two wells located in fine to medium sand contaminated with oil (product density ranges between 0.75 and 0.83, and product viscosity is 20 cP). The oil transmissivity obtained is in good agreement with the bail-down interpretation method and the analytical model.

These studies indicate that for conditions that are different from the conditions of our studied site, bail-down tests may give good results as long as interpretation method assumptions are verified during the test. Huntkey and Kolhatkar studies are especially interesting as both

shows that bail-down tests are still valid for products with lower viscosity than our study site, as long as the medium permeability is low enough to also keep the overall hydraulic oil conductivity also low. To assess whether the hydraulic oil conductivity below a minimum value introduces an error when interpreting a bail-down test in a two-phase system, and to assess the range of the error, the test should be numerically simulated. This approach would allow different soil and oil types to be combined.

Finally, this study addresses some issues brought up in the discussion opened by Batu (2012) focused on i) the Huntley's simplifying assumption (Huntley, 2000) for drawdown calculation (assumption b.4 of Section 2.2), ii) the modification of the Thiem equation by Huntley (2000) and Lundy and Zimmerman (1996), and iii) the range of the initial oil drawdown ($s_{o(0)}$) as compared to the oil thickness in the formation.

Huntley (2000) simplifying assumption for the drawdown calculation states that the total potentiometric surface remains constant during the test. This assumption is critical as it allows Huntley (2000) to introduce his density factor $1/1 - \rho_o$ and to obtain the Equation 2.57 that gives a solution to calculate the oil transmissivity using this solution derived from Bouwer and Rice (1976). Batu (2012) is concerned by the fact the Huntley's paper (Huntley, 2000) presents limited field data to support his assumption. This study answers Batu (2012) concern by testing the Huntley's assumption (Huntley, 2000) over 289 bail-down tests. It clearly shows that the Huntley's assumption to calculate the oil drawdown (Huntley, 2000) is satisfied for 96% of the data tested. However, it is important to mention that the validity of this assumption is closely related to the site conditions and to the nature of the product (coarse-grained size distribution, heavy and viscous oil). The study of the groundwater fluctuation shows that the Lundy and Zimmerman's simplifying assumption (assumption b.3 of Section 2.2) which assumes that the oil/water interface is not moving during the test (Lundy and Zimmerman, 1996), and has only been observed for 4% of the data tested, is true when oil is in the aquifer under a confined condition. The valid simplifying assumption for the oil drawdown calculation is obviously hard to predict even if unconfined viscous oil in a fairly permeable aquifer are likely to be the conditions that make the Huntley's assumption valid, whereas confined oil below a fine-grained layer or less viscous oil are the conditions usually encountered when the Lundy and Zimmerman's simplifying assumption is satisfied. This debate around the oil drawdown calculation is interesting from a theoretical point of view as it makes the widely used modified Bouwer and Rice solutions (Lundy and Zimmerman, 1996; Huntley, 2000) valid or not dependent on the specific site conditions and the nature of the product. However, for a practical point of view, the further modification of the Bouwer and Rice solution proposed by Kirkman (2013) introducing the *J - Ratio* is the solution that should be used as it applies regardless the behavior of the total potentiometric surface or of the oil/water interface.

Another point introduced by Batu (2012) is related to the range of the initial oil drawdown as compared to the oil thickness in the formation. In their solution Bouwer and Rice (1976) assume that the initial water drawdown is very small as compared to the saturated aquifer thickness. This assumption is critical and needs to be verified to make the solution valid. In the modified Bouwer and Rice solutions (Lundy and Zimmerman, 1996; Huntley, 2000; Kirkman, 2013) this assumption is also critical which means that the initial oil draw-

down has to be very small as compared to the thickness of the aquifer where oil saturation exists. The good outcome of this study regarding the results obtained using the Huntley solution means that this assumption was verified during the tests. This may be explained by the high viscosity of the oil (more than 80 cP) which reduces the oil hydraulic conductivity, and therefore bailing out the oil from the well triggers a very small oil drawdown in the adjacent formation around this well. However, the Batu concern regarding the fact that this critical assumption may not be verified during a bail-down test in a two-phase system is valid. This study gives answers for specific site conditions and nature of the product and its conclusions cannot be applied to other conditions. Therefore, it is important for the practitioners to estimate the oil transmissivity applying solutions based on different boundary conditions and assumptions in order to assess if critical assumptions are met with the field conditions of his study.

Groundwater fluctuation

This study confirms that, in unconfined aquifers, the oil thickness measured in the monitoring wells is largely impacted by the groundwater table fluctuation. This situation leads to the fact that the oil within the well and in the formation are permanently under non-equilibrium conditions, and even after 5 months of a fairly stable groundwater table, oil flows between the well and the formation still occur in same wells to equilibrate the system. Therefore, the oil thickness in the monitoring well does not represent the oil thickness in the adjacent formation, and short-term measurement of the oil thickness in monitoring wells cannot be interpreted. However, long-term measurement of the oil thickness in monitoring wells along with the groundwater fluctuation is a good diagnostic approach to:

- Define the nature of the soil around the wells and the confining situation (unconfined or semi-confined).
- Estimate the oil thickness in the formation if a long period of stable groundwater table is observed or applying the model proposed in this study.
- Potentially estimate the hydraulic conductivity of the oil in the formation.

The nature of the soil and the conditions in which oil is present in the formation are two aspects that can be determined from the observations of the oil/air and oil/water interface variations, and from the oil thickness versus oil/water interface level curve. This analysis does not require the interface levels to be automatically measured. On the contrary, to estimate the oil thickness in the formation and the oil conductivity, automatic data acquisition is necessary. Interface variations have to be recorded during several months to gather data regarding significant variations of groundwater level. A full year would be ideal to increase the opportunity to obtain datasets over a significant period with limited groundwater table movements.

Model for Estimating the Oil Thickness in the Formation and the Hydraulic Oil Conductivity

The model developed and tested in this study for oil present under unconfined, and also under semi-confined conditions, gives good results for estimating the oil thickness in the aquifer and the hydraulic oil conductivity, whereas the applied simplifying assumptions considered a constant oil saturation and hydraulic conductivity across the oil layer which is not aligned with the multi-phase model proposed by Parker (1989) and Farr *et al.* (1990). As already mentioned, these models rely on homogeneous and equilibrium conditions to describe the vertical distribution of the fluid saturations and relative permeabilities. Although, Huntley *et al.* (1992) showed that measured oil saturation profiles differ from saturation profiles predicted by those models. The main reason is the heterogeneity of the formation that leads to sharp variation in the oil saturations between layers with different grain sizes. From analysis on soil core borings, Huntley *et al.* (1992) shows that oil saturation is the highest in one or two layers, and largely lower in the rest of the formation where oil is present. Therefore, it can be assumed that the hydraulic oil conductivity of the layer is mainly dependent on the hydraulic oil conductivity of the layers with the highest oil saturations. In these layers, the oil saturations and the hydraulic oil conductivity are likely to be constant. So, it minimizes the error introduced by the model assumptions and may explain why the model works even if fundamentals of the multi-phase models are not accurately followed. Thus, it is likely that uncertainties of the model may grow in homogeneous medium. Last, the model has been tested for two sets of data and compared to bail-down test results that have not been performed exactly at the same period. Therefore, to validate the model, it would be necessary to compare estimated hydraulic oil conductivity for a larger number of data set, and with bail-down test results performed during the same period.

Relationship Between Bail-down Test and Groundwater Fluctuation

Considering the impact of the groundwater table fluctuation on the oil thickness in the monitoring wells, it is important to link the potential impact of this fluctuation on the bail-down test results. Actually, the measured oil mobility may not be the same for different groundwater table levels. If we consider i) the fact that the vertical distribution of the oil saturation may present sharp changes as mentioned above and, ii) that the hydraulic oil conductivity value obtained from bail-down test is an average of the hydraulic oil conductivity of each layer across the oil phase in the formation. Therefore, the impact of the groundwater fluctuation on the bail-down test results will be driven by the position of the oil/water interface in the well as compared to the layer which presents the highest hydraulic oil conductivity. Considering the exemple presented in Figure 5.1, the oil transmissivity obtained from a bail-down test will be the highest when the oil/water interface is below the layer I, and will decrease when the oil/water interface moves up.

Therefore, it is recommended to perform a bail-down test during the period of the lowest groundwater level in order to obtain an oil transmissivity that accounts for all the most permeable layers where oil is present. Last, when bail-down tests are performed over several years, it also would be ideal to do the tests when the groundwater is for the most part consistently at the same level, so the results can be compared.

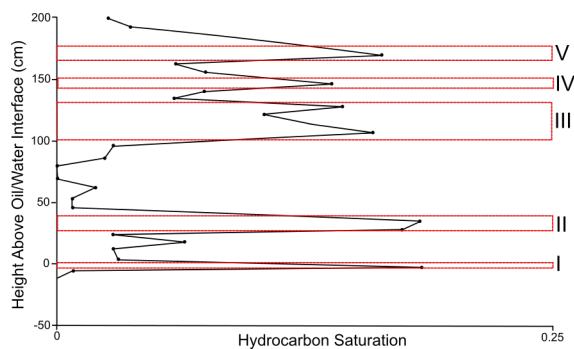


Figure 5.1: Example of measured oil saturation profile showing sharp changes (after Huntley *et al.* (1992)). Layers noted I to V represents the layers where the hydraulic oil conductivity is the highest

Impact on Project Management

Key Outcomes for Assessing an Oil Issue in the Subsurface

When a site use history identified a potential oil contamination, it is necessary to understand the nature of the product, along with its extent, behavior and mobility in the subsurface. This understanding will require several investigation techniques to be applied. In the past, the implementation of monitoring wells to delineate and understand the issue was commonly used. The rotary drilling technique to install wells does not allow an understanding the oil vertical distribution. It is therefore necessary to collect soil core borings in the same location where the monitoring wells are installed to understand of the oil vertical distribution and oil quantity at depth. In geological context with fined-grained soil, both actions can be combined. The well can be drilled using percussion techniques that allow the collection of soil cores during the well drilling process. However, the investigation approach involving only soil core boring and monitoring wells is often less-cost-effective.

Over the last years, screening techniques coming from the petroleum industry have been developed for soil and groundwater investigation purposes. For oil contamination, the Laser Induced Fluorescence (LIF) is especially of key interest as it gives a qualitative view of the horizontal and vertical distribution of the oil. This technique allows to cover 50 to 100 linear meters within a day depending on the soil nature and how easily the tool can penetrate the soil. Therefore, a cost-effective approach is to combine these techniques. The LIF allows its user to quickly define the extent of the oil contamination, and then, monitoring wells and soil core borings are used to quantify the oil content and investigate its mobility. Typically, performing a first screening of the potentially contaminated area with LIF allows to significantly reduce the number of wells and to target those wells in the areas of concern.

Regardless the investigation strategy selected, the present study shows that a simple approach measuring the oil thickness is not sufficient to conclude on oil volume and mobility. Furthermore, solely using the oil thickness measured in monitoring wells may lead to substantial error when designing an oil collection network.

The main reasons are:

- oil thickness in a monitoring well is closely linked to the grain size distribution of the adjacent formation. The Parker model, which defines the oil thickness in the well

depending on the physical properties of the adjacent soil, shows that for the same quantity of oil in fine sand or gravel, oil thickness in the wells varies significantly.

- oil thickness in a monitoring well is closely linked to the condition in which the oil is present in the soil. In an unconfined condition the oil thickness in the monitoring well does provide a good indication of head whereas a confined condition results in a misleading oil thickness.
- in a context of groundwater fluctuation, the oil thickness in the monitoring wells is not reliable information. As shown by Kemblowski and Chiang (1990), Marinelli and Durnford (1996) and Aral and Liao (2002), this study confirms that the groundwater fluctuation significantly impacts the oil thickness in the monitoring wells. A well may exhibit 2 m of oil in summer, when groundwater table is low and no oil at the end of the fall, when groundwater is high. Therefore, an oil thickness measured at time t in a monitoring well cannot be interpreted outside a complete chronology of groundwater fluctuation and oil thickness in this monitoring well.

As suggested by the ASTM E2856-13 guideline, for an optimal design of an oil collection system, it is necessary to assess the oil mobility in order to target the most productive areas. This study confirms that the oil mobility assessment should be performed using bail-down test interpreted by one of the following methods: the modified Bouwer and Rice (Kirkman, 2013), the modified Cooper (Beckett and Lyverse, 2002) and the modified Jacob and Lohman (Huntley, 2000) methods. As these techniques are based on graphical interpretations which are not extremely precise, it is suggested to use at least two of the techniques and to consider the mean value. Depending on the quantity of wells considered for bail-down testing, it would be valuable to use automatic acquisition of the interface levels in order to maximize the quantity of interpretable datasets. As an example, performing ten bail-down tests with manual measurements will take several weeks, and the groundwater table may have changed over that period. Therefore, the oil transmissivities obtained from the tests at the beginning cannot be compared to those obtained at the end of the period. The automatic data acquisition is, in this case, the most appropriate approach to gather useful data for future remediation design. However, both manual and automatic data acquisition may be used depending on the site conditions, the quantity of measurements to be performed and the objective.

Due to the important impact of the groundwater fluctuation on the oil thickness and mobility, it is necessary that the measurements are part of a long-term program. Furthermore, it seems inappropriate to conclude on a oil collection system design without a dataset that cover a complete year of seasonal groundwater table fluctuation. To understand in which condition the oil is present accross the investigated area (i.e.: confined, unconfined or perched), and to assess the impact of the groundwater table fluctuation on the oil thickness, a monthly manual measurement should be sufficient. Automatic data acquisition is recommended to assess the oil thickness in the formation, and its transmissivity. The transmissivity values should be compared to those obtained from bail-down tests.

Table 5.3 summarizes the main approach for investigating an oil issue.

Table 5.3: Main Investigation Techniques for Understanding an Oil Contamination

Investigation Technique	Measurements/Sampling	Purposes
Laser Induced Fluorescence	Qualitative oil concentration profile at depth	- Confirm the presence of oil - Qualitative horizontal and vertical oil distribution
Monitoring wells	- Oil Thickness variations over a year - Bail-down tests - Product sampling - Groundwater sampling	- Oil condition in the subsurface - Oil transmissivity - Product physical properties - Dissolved phase quantification for risk analysis
Soil core boring	- Grain sizes - Oil concentration	- Vertical grain size distribution - Oil vertical distribution at depth

Key Outcomes for Optimizing a Oil Recovery Project

The overall efficiency of an oil recovery project is based on i) the initial design of the system, ii) the alignment of the design and of the applied recovery technique over time, and iii) a good operational management.

Oil Recovery System Design

The design of the system includes the choice of the recovery technique and the location and quantity of wells that will be implemented. The commonly used recovery techniques include the static skimming, the dynamic skimming and the vacuum enhanced extraction. Decisions around the design are largely based on the data collected during the investigation phase. Regarding the location of the extraction wells, this study confirms that the approach usually observed in Europe, to place recovery wells based on the oil thickness in monitoring wells, may lead to an inefficient design. Therefore, it is recommended that the recovery well locations be determined based on the oil transmissivity values. Areas showing greater oil transmissivity values should be targeted, and a maximum of extraction wells should be installed there. On our studied site, the wells showing the greater oil transmissivity are randomly distributed across the oil lenses and should lead to focusing the extraction wells around these locations. Therefore, a design with groups of closely spaced recovery wells would be more efficient than a design with lines of wells uniformly distributed across the oil lenses.

Regarding the quantity of wells and the distance between wells, the most practical approach would probably be to densify as much as possible the number of recovery wells, considering technical constraints of the site. This approach is recommended for two main reasons. First, the other approach would be to apply the Parker *et al.* (1987) model for estimating the recovered volume over the time for different scenarios. But, as shown in this study, the heterogeneous conditions encountered on the sites and the permanent non-equilibrium conditions introduce significant uncertainties in this approach. Secondly, it is less costly to install more recovery wells to minimize the time of the project than to operate

the recovery system for a longer period of time with less recovery wells. This cost difference is essentially based on the rental cost of the extraction unit, on the waste disposal cost, on the energy cost and last, on the cost for the technician who maintains the system.

The choice of the technique is driven by parameters other than the oil mobility. The nature of the product is a first parameter to consider. For example, if the oil creates an emulsion when pumped with water, vacuum extraction will not be considered as the treatment of the emulsion will trigger significant costs. Another parameter is the groundwater quality at depth, beneath the oil contaminated area. If the groundwater is contaminated, it may jeopardize the possibility for dynamic skimming as upstream re-injection would not be an option, and therefore water will have to be treated. Another key parameter which should be considered to determine the most appropriate technique is the oil thickness in the wells. To minimize the quantity of water collected by the system, it is typical to adjust the skimmer position leaving between 5 and 10 cm of oil beneath the skimmer, so the initial oil thickness should be sufficient (typically 30 cm) to allow for this adjustment. It is thus important to consider the change in oil thickness over a sufficient period to decide which technique should be considered. If the oil thickness is often lower than 30 cm, it would be better to consider a dynamic skimming approach to enhance the oil flow to the well, and minimize the water pumping with the skimmer. Or, if the mobility is low, passive techniques, like oleophilic belts are more appropriate. In any case, a final decision on the remediation technique should be taken after having performed a pilot test, which is a small scale field test of the technique to validate the assumption and fine-tune the design.

Efficiency Follow-up, Design Alignment and Operation Management

In addition to serving as a parameter to design an oil recovery project, the oil mobility should also be assessed over time to define the efficiency of the current recovery system and to make adjustments. A yearly program of bail-down tests should be performed in wells across the remediation area to confirm the decrease of the oil transmissivity. Due to the potential impact of the groundwater table variation on the oil mobility, it is recommended to conduct the bail-down test campaign when groundwater is close to the level it was when the test was originally performed before the start of recovery. The study shows that the system takes a while to equilibrate, therefore, if a bail-down test is performed in a recovery well, it is important to stop the recovery system well in advance to allow time for equilibration. However, it may be difficult to meet both conditions: a long-time for equilibration and a groundwater table within the targeted range of values. It is therefore recommended to implement monitoring wells across the remediation area which will allow the test to be performed at the best period, without waiting for the system to equilibrate. The other advantage is that these monitoring wells will allow to assess radius of influence of the recovery system, and to adjust the design if required. To perform this assessment, it is better to place the monitoring wells in the center of the remediation areas and at several distances from the recovery wells.

In term of operation, it is clear that the impact of the groundwater fluctuation has to be considered to optimize the operation. Figure 5.2 shows the impact of the groundwater fluctuation on the recovery rate of the system on our studied site in 2015.

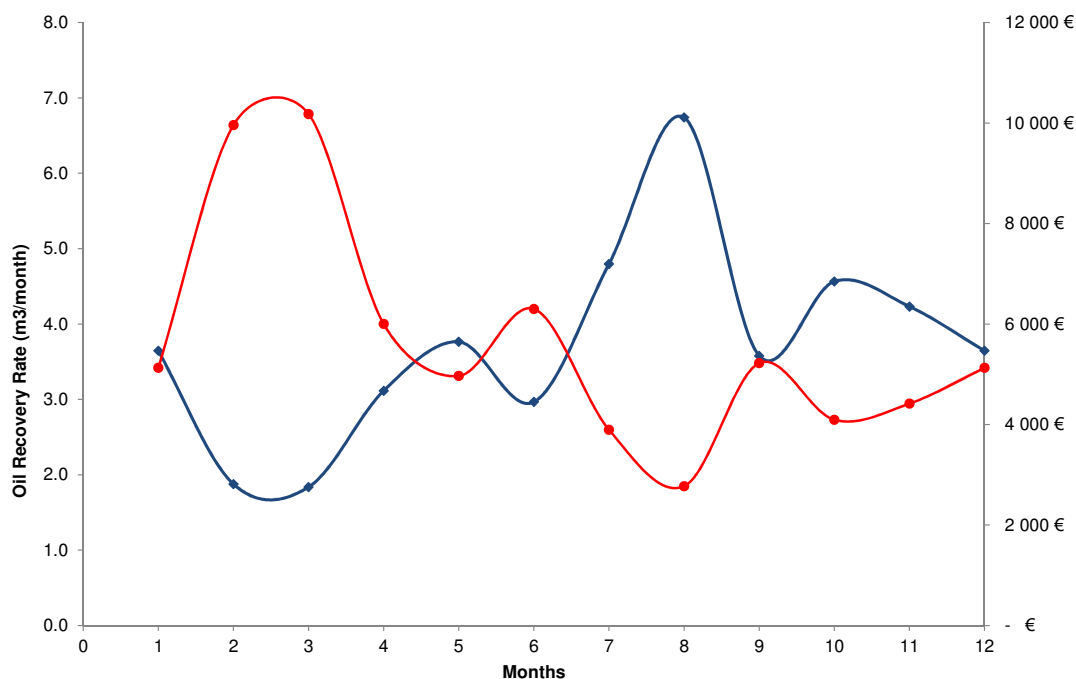


Figure 5.2: Monthly variation of the oil recovery rate (blue curve) due to groundwater table fluctuation, and monthly evolution of the cost to recover one cubic meter of oil (red curve) in 2015

The recovery rate variation is directly linked to the oil thickness in the monitoring wells and to the oil transmissivity. For an homogeneous medium, the recovery rate decrease should be linear when groundwater table raises (and oil thickness in the wells drops). For heterogeneous formations, the extraction rate variation depends on the position of the oil/water interface as compared to the position of the layer where the hydraulic oil conductivity is greater. As illustrated on Figure 5.3, the optimal recovery rate is obtained when the oil/water interface in the recovery well is lower than the deepest layer with a significant hydraulic oil conductivity. This optimal position should be assessed well by well.

It is clear that the oil recovery follows the seasonal fluctuation of the groundwater table variation, with a maximum of extraction during the summer period. This variation of the extraction rate implies that the cost of a cubic meter of oil recovered in winter is significantly (5 times) higher than the cost for a cubic meter of oil recovered in summer. This cost difference is due to the fixed cost of the remediation which covers the material rental and the personnel. To minimize this effect and increase the efficiency of the system, it could be considered to switch from static to dynamic skimming during the period when the groundwater table is high. In some cases, that approach would allow to decrease the level of the oil/water interface below the layers where the hydraulic oil conductivity is the greatest and artificially maintain a reasonable extraction rate. Another approach, depending on the remediation contract and government/Environmental Agency obligations, would be to switch-off the system when the oil recovery rate is lower than a certain level.

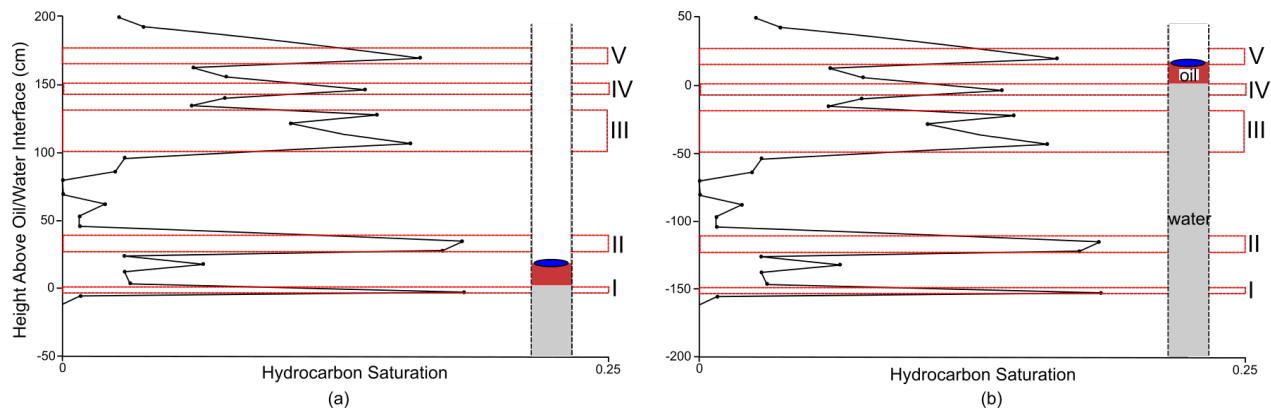


Figure 5.3: Oil skimmer (in blue) position in the recovery well, depending on the position of the groundwater table. Scenario (a), the groundwater level is low and the skimmer position allows to recover the oil that flows from the layers (I to V) where the hydraulic oil conductivity is the highest. Scenario (b), the groundwater level is high and the skimmer position allows only to recover the oil from layer V.

Estimation of the project duration

Applying LDRM model (Charbeneau, 2003) based on a certain design and before the oil recovery start, may give directional estimation of the duration, but with significant uncertainties. However, after a sufficient period of recovery, datasets such as the oil thickness in monitoring wells when groundwater table is low and oil mobility, may allow to fit the model and refine the estimation of the project duration. Another approach would be to apply a numerical model for transport.

The parameters to decide when to stop the project depends on several factors which includes Environmental Agency requirements or company practices. It is clear that a end-point should be fixed as oil recovery projects may extend over years or decades. The reason for that is over time an asymptote of treatment is reached, and this period is characterized by a very low recovery rate may take decades depending on site conditions. Even if a specific value of the oil mobility would be a logical aspect to consider for the end-point of the treatment, it is obviously hard to determine for each soil type and technique applied, what is the value of the hydraulic oil conductivity that should be reached before stopping the system. Therefore, the proposed approach is more practical, and considers the oil thickness in the recovery wells, after equilibration time. It seems logical to stop the skimming approaches if the oil in the recovery well is lower than 30 cm when the groundwater table is at its lowest level. In that case, other end of treatment techniques may be considered with oleophilic belts or manual pumping.

Table 5.4 summarizes the proposed improvements to the standard approach for managing a oil recovery project in Europe.

Table 5.4: Classical approach for the main oil recovery project steps in Europe and proposed improvement based on the present study outcome

Project Step	Standard Approach in Europe	Proposed Improvements based on present study outcome	Gain
Defining the nature and extent of the oil issue	<ul style="list-style-type: none"> - Monitoring wells implementation - Physical and chemical analytics of the product sampling - Oil thickness measurements once in all the wells, and on a quarterly basis in some selected ones - Bail-down test in few wells once 	<ul style="list-style-type: none"> - Oil thickness measurements at least once a month over 6 months in all the wells - Automatic data acquisition of the groundwater table fluctuation in a well outside the oil lenses - Automatic data acquisition of the oil thickness in a significant number of wells, randomly distributed within the contaminated area - Bail-down test in all the wells when groundwater table is low 	<ul style="list-style-type: none"> - Accurate understanding of the groundwater impact - Assessment of the depth and thickness of the oil in each areas - Accurate oil transmissivity values allowing identification of the most productive areas - Have a clear baseline condition which will be the basis for assessing the efficiency of
Estimation of project duration	<ul style="list-style-type: none"> - Often not estimated 	<ul style="list-style-type: none"> - Estimate prior to the remediation start for directional indication. Yearly refinement based on data collected 	<ul style="list-style-type: none"> - More accurate duration estimate of the project
Efficiency follow-up	<ul style="list-style-type: none"> - Oil thickness follow-up in monitoring wells or recovery wells 	<ul style="list-style-type: none"> - Monthly oil thickness in the monitoring wells and yearly bail-down test in all the wells at the same groundwater level than prior remediation tests 	<ul style="list-style-type: none"> - Strong efficiency evidence
Decision to stop the system	<ul style="list-style-type: none"> - Asymptote of treatment is the common arguments 	<ul style="list-style-type: none"> - Stop when oil thickness < 30 cm for low groundwater table 	<ul style="list-style-type: none"> - Optimized used of the automatic skimming approach

Conclusions

The outcomes of this study improve the use of the investigation data to better define the design of an oil recovery project, to improve the management of the technical aspects over the duration of the cleanup actions, and to anticipate the duration of the recovery. In particular, this study outlines:

- The validity of the bail-down test to estimate the oil transmissivity in a two-phase system. This is an important outcome as the oil mobility is a key parameter to consider when designing an oil recovery system. It is also a good parameter to follow-up the efficiency of the system over the treatment year. Last, the bail-down test datasets give good indication of the nature of the formation around the well, and of the oil mass conditions in the formation.
- The areas showing the greatest oil mobility values are randomly distributed across the studied site and does not agree with the areas showing the greatest oil thickness. It confirms that the approach which rely on oil thicknesses in monitoring wells for designing an oil recovery project is not the best practice to follow. However, the oil thickness remains an important parameter to consider to define the appropriate recovery technique.
- Groundwater table fluctuation has a great impact on the oil thickness in the monitoring wells and, its understanding and follow-up would allow to assess in which conditions the oil mass is present on a study site (i.e.: unconfined or semi-confined), to define the position and the vertical movements of the oil layer in the formation, to estimate the hydraulic oil conductivity in the formation, and overall to improve the oil recovery system.

The study on the bail-down test validity has been conducted with heavy viscous oil in permeable formations. The conclusion of this study on the bail-down test validity for two-phase system cannot be extended to a wider range of LNAPL and formations with different properties. One approach to define potential limits of the bail-down test validity would be to perform numerical simulations. This would allow to test different combinations of product and formation properties. During this work simulations have been made in collaboration with Stuttgart University. DUMUX ¹ (DUNE for Multi Flow and Transport in Porous Media) was used to simulate the vertical and radial distribution of LNAPL in a radially symmetric domain. This work allowed to establish the numerical model parameters (i.e.: boundary conditions, grid design, etc...). Encouraging results have been obtained, however more time would be required to finalize the work as discrepancies remain between the modeled and measured bail-down data.

As data were available from the studied site before and 2 years after the remediation start, the initial intention was to refine the timing estimation of a recovery project applying LDRM model (Charbeneau, 2003). Unfortunately, the recovery volume was recorded for the

¹DUNE for Multi Flow and Transport in Porous Media <http://www.dumux.org>

entire system (120 wells) and not for each well. Applying LDRM for the whole site did not allow to adjust the model, due to heterogeneity. Individual flow meters should be installed over the coming months, it will thus be interesting to adjust the model for each well with measured oil thicknesses and with oil transmissivity, inferred from bail-down tests.

Finally, the impact of groundwater table fluctuations was the last part of the study. It has been conducted i) on a limited number of wells due to the small amount of automatic probes available at that time and, ii) not at the same period in which the bail-down tests were conducted because we never thought that we could estimate the hydraulic oil conductivity from this parameter. Therefore, few field tests were available to validate the proposed model for estimating the hydraulic oil conductivity. It is therefore suggested that further assessment is made to confirm the approach, especially for semi-confined oil layer conditions.

Concerning the set up and following of the remediation, the present study gave several indications, by insisting, among other points, on the need of numerous wells and a thorough characterization of the oil lenses with bail-down tests. Due to the lack of time and to the averaging of oil abstraction measurements, it was not possible to draw major conclusions for the optimization of the different phases of the remediation project. We think that some research points remain to make such improvements. That would include:

- A better understanding of the link between the grain size and the oil mobility in field conditions, this could be addressed by a combination of detailed characterization in the field, pilot tests and numerical modelling.
- Analysis of the vertical distribution of the oil permeability. Indeed the few detailed studies insist on the presence of a transmissive layer that plays a major role. The follow up of oil variations combined with thin vertical sampling may give such results.
- A detailed analysis of the link between the oil mobility and the groundwater table variation and a review of when to use dynamic or static skimming. This would require the detailed follow up of several wells with different techniques.

Appendix A

Bail-down Test Field Note

Avant écrémage/nettoyage		Ecrémage avant mesures		Commentaires/Remarques	
Heure		Heure	06:25	Commentaires : Densité : Couleur : Huile rouge Aspect : Pas d'émulsion Photo	
Profondeur HC (m)		Profondeur HC (m)	-2.230		
Profondeur eau (m)		Profondeur eau (m)	-2.320		
Epaisseur huile (m)		Epaisseur huile (m)	0.090		
Durée écrémage (min)		Durée écrémage (min)	1		
Volume total pompé (L)		Volume total pompé (L)	0.9		
Volume eau pompé (L)		Volume eau pompé (L)	0		
Volume écrémé (L)		Volume écrémé (L)	0.9		

Date	Heure	Temps (hh:mm)	Profondeur huile (m)	Profondeur eau (m)	Epaisseurs d'huiles (m)	Graphes
01/02/16	6:27	0:00	-2.250	-2.250	0.000	
01/02/16	6:28	0:01	-2.250	-2.250	0.000	
01/02/16	6:29	0:02	-2.250	-2.250	0.000	
01/02/16	6:30	0:03	-2.250	-2.255	0.005	
01/02/16	6:31	0:04	-2.250	-2.255	0.005	
01/02/16	6:32	0:05	-2.250	-2.255	0.005	
01/02/16	6:37	0:10	-2.250	-2.255	0.005	
01/02/16	6:42	0:15	-2.245	-2.255	0.010	
01/02/16	6:57	0:40	-2.245	-2.255	0.010	
01/02/16	7:27	1:00	-2.245	-2.255	0.010	
01/02/16	10:20	3:42	-2.250	-2.270	0.020	
01/02/16	14:27	8:00	-2.230	-2.270	0.040	
01/02/16	18:27	12:00				
02/02/16	22:27	16:00				
02/02/16	2:27	20:00				
02/02/16	7:15	24:00	-2.200	-2.280	0.080	
02/02/16	12:27	30:00	-2.195	-2.280	0.085	
02/02/16	18:27	36:00				
03/02/16	6:27	48:00				
03/02/16	18:27	60:00				
04/02/16	6:27	72:00	-2.200	-2.320	0.120	
05/02/16	6:27	96:00				

MATERIEL	
Type de Pompe :	SOLINST S130
Réglage du skimmer (g)	

Figure A.1: Field Note Form for the Bail-down Test

Appendix B

Paper published in *Groundwater and Monitoring Journal*

Comparison of Oil Transmissivity Methods Using Bail-Down Test Data

by Cédric Palmier, Matthew Dodt, and Olivier Atteia

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

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 criti-

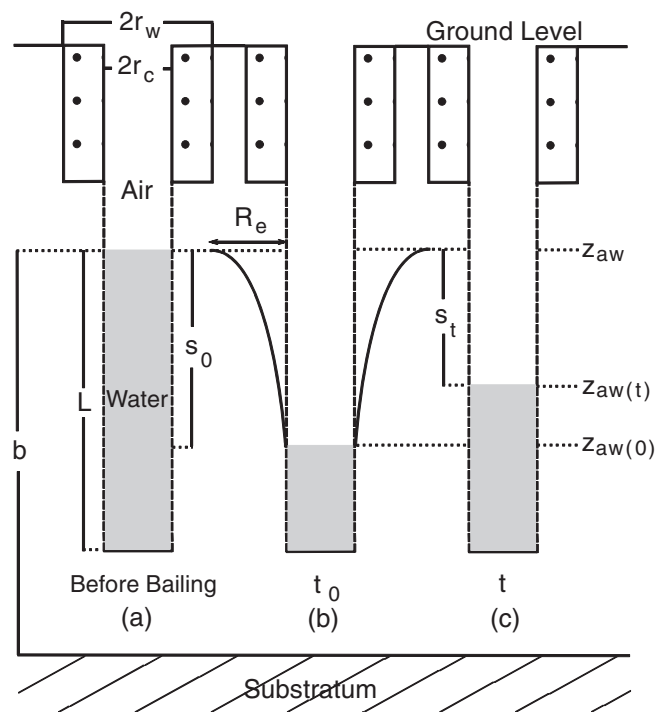


Figure 1. Geometry of partially penetrating wells in a water system (a) before water bailing, (b) at time t_0 , and (c) at time t_1 after water bailing.

cal 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.

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

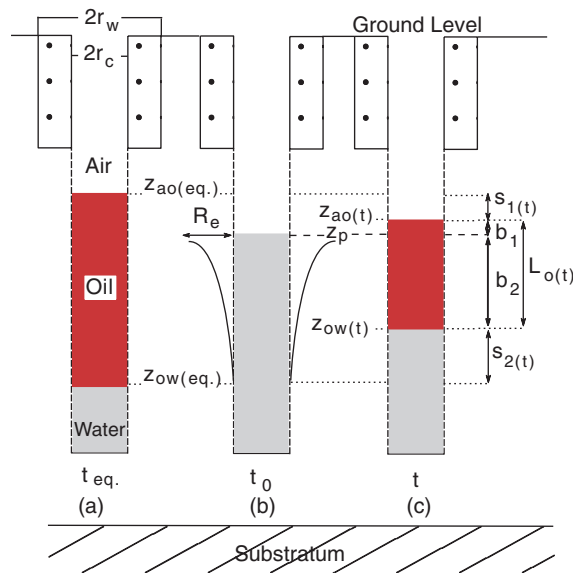


Figure 2. Geometry and symbols of partially penetrating wells in an oil/water system (a) at the equilibrium conditions, (b) at time t_0 , and (c) at time t_1 after oil bailing.

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.

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

where J is the J-ratio defined by:

$$J = \frac{\Delta s_n}{\Delta b_n} \quad (6)$$

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	<ul style="list-style-type: none"> 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. 	$T_o = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2} \frac{1}{t} \ln\left(\frac{s_{1(0)}}{s_{1(t)}}\right) \quad (1)$
Bouwer and Rice-modified solution. Huntley 2000	<ul style="list-style-type: none"> 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. 	$T_o = \frac{r_c^2 \left(\frac{1}{1-\rho_o}\right) \ln\left(\frac{R_e}{r_w}\right)}{2} \frac{1}{t} \ln\left(\frac{s_{1(0)}}{s_{1(t)}}\right) \quad (2)$
Cooper et al.-modified solution. Beckett and Lyverse 2002	<ul style="list-style-type: none"> Confined aquifer with fully penetrating well. Resulting oil transmissivity values need to be multiplied by the oil density correction factor $(1/1-\rho_o)$. 	$\frac{z_{ao(t)}}{z_{ao(0)}} = 8\alpha / \pi^2 \int_0^\infty e^{-\beta u^2 / \alpha} du / (u \Delta(u)) \quad (3)$ <p>where $\alpha = r_c^2 S / r_w^2$ and $\beta = T_o t / r_w^2$</p>
Jacob and Lohman-modified solution. Huntley 2000	<ul style="list-style-type: none"> Oil recovery is assumed to be slow enough to consider a pseudo steady-state condition. 	$\sum_{i=1}^n (s_i \Delta t_i) = \frac{2.3}{4\pi T_o} \sum_{i=1}^n \left(Q_i \Delta t_i \log \frac{2.25 T_o t_i}{r_c^2 S} \right) \quad (4)$

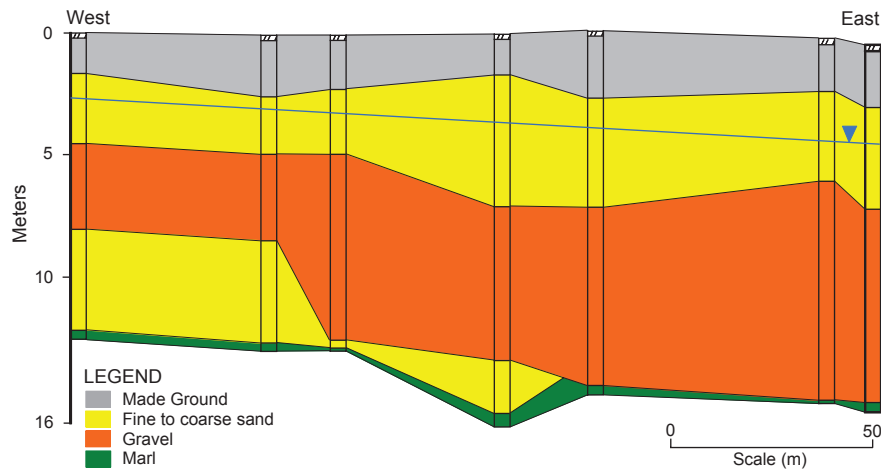


Figure 3. West to East schematic cross section of the local upper strata.

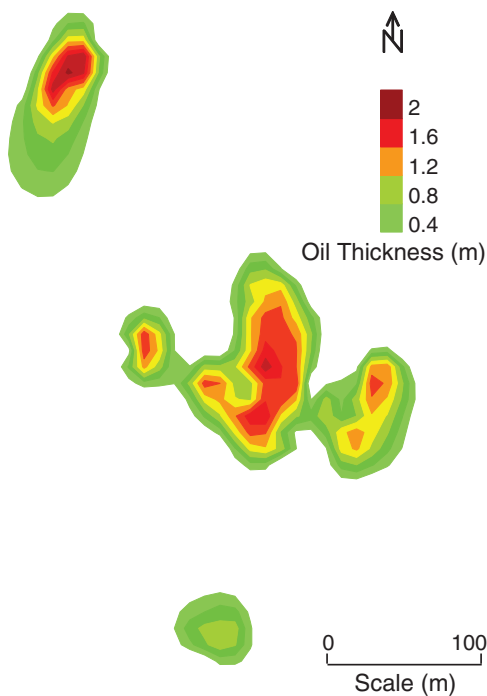


Figure 4. Distribution and thickness of the oil in meters using kriging interpolation at t_0 .

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 $15,000$ m². The oil thicknesses measured in 120 wells ranged from a few centimeters to 2.5 m (Figure 4). Due to the long history of

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

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.

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 m³ oil storage capacity. Ten other wells are distributed across the oil collection areas for monitoring purposes. After 18 months of extraction, 90 m³ 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 30cm 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 30cm 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 m³/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 potentiomet-

ric 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_0 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) ($R^2_{J\text{-ratio}} > 0.8$)			Good Correlation (Type 2) ($0.8 > R^2_{J\text{-ratio}} > 0.5$)			Limited Relation (Type 3) ($R^2_{J\text{-ratio}} < 0.5$)		
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

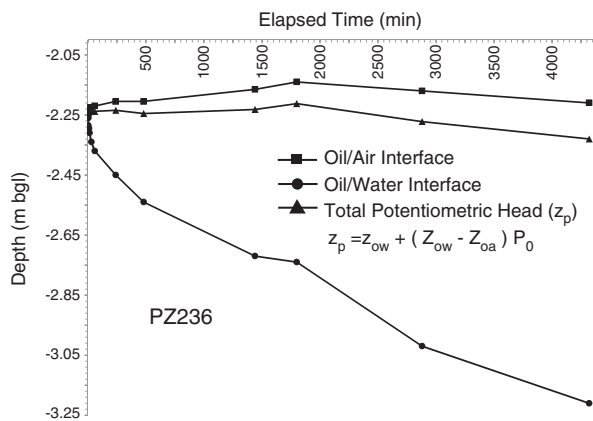


Figure 5. An example of oil/air and oil/water interface levels during the test (PZ 236).

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,

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

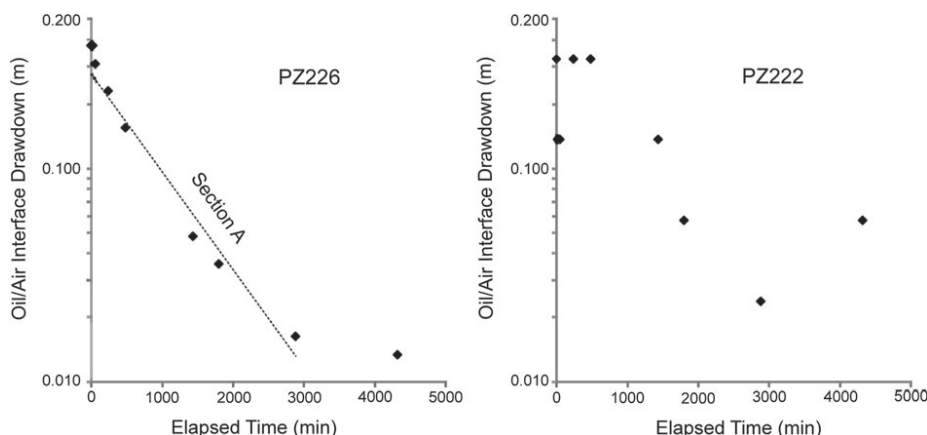


Figure 6. Bail-down test data sets for piezometers PZ 222 and 226 at t_0 .

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,

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

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'								
	$R^2_{J\text{-Ratio}} > 0.8$			$0.8 > R^2_{J\text{-Ratio}} > 0.5$			$R^2_{J\text{-Ratio}} < 0.5$		
	$J = -(1 - \rho_o)$ (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

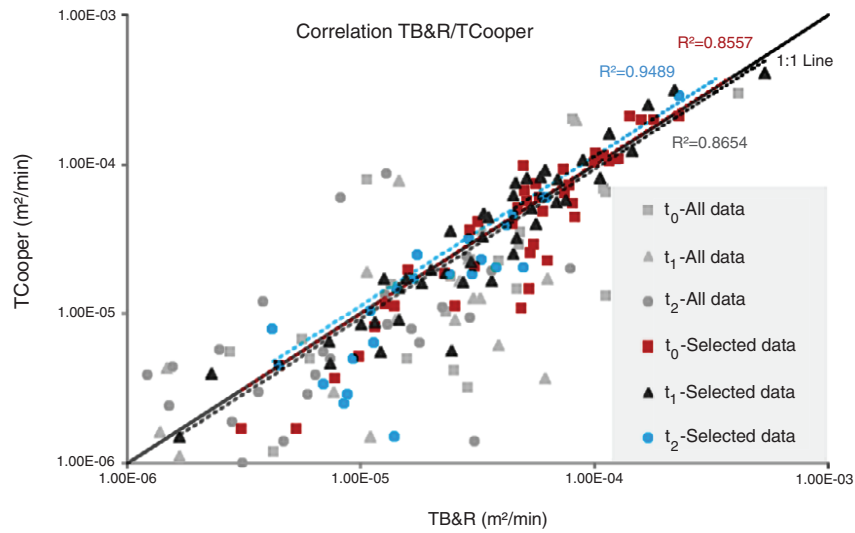


Figure 7. Correlation between the oil transmissivity values estimated by the modified Bouwer and Rice approach and by the modified Cooper et al. approach.

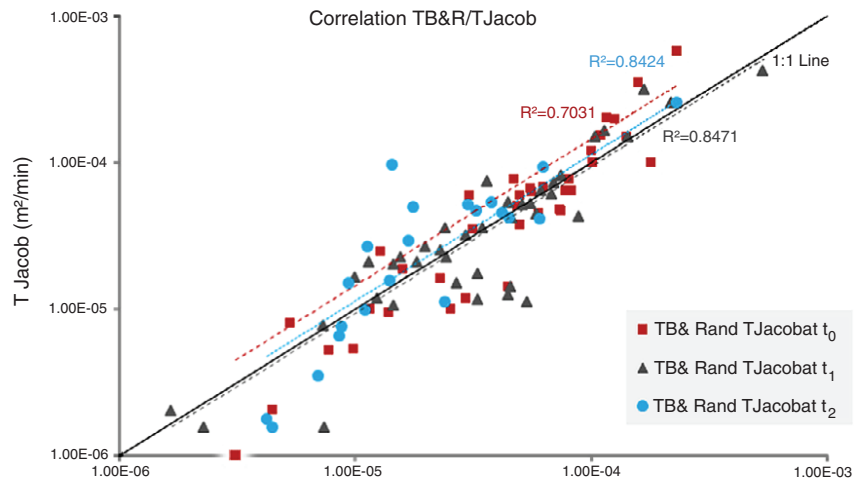


Figure 8. Correlation between the oil transmissivity values estimated by the modified Bouwer and Rice approach and by the modified Jacob and Lohman approach.

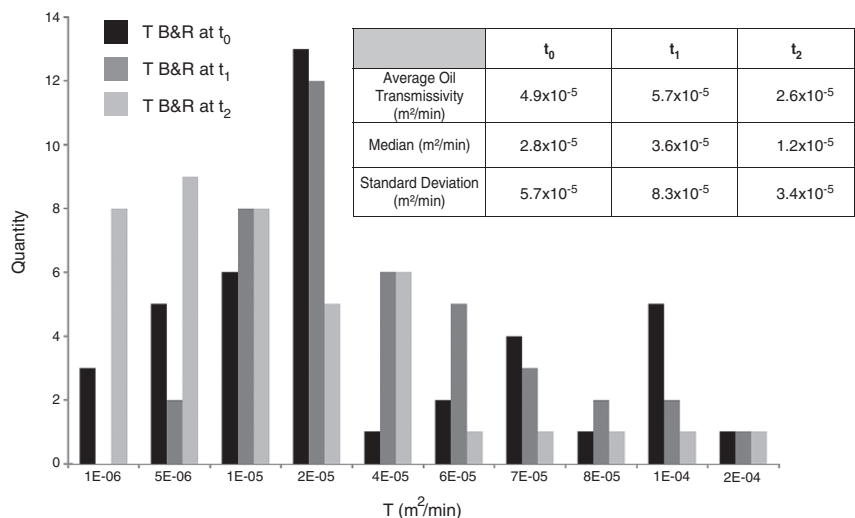


Figure 9. Oil transmissivity values and main statistics before, 6 months after, and 18 months after start of remediation.

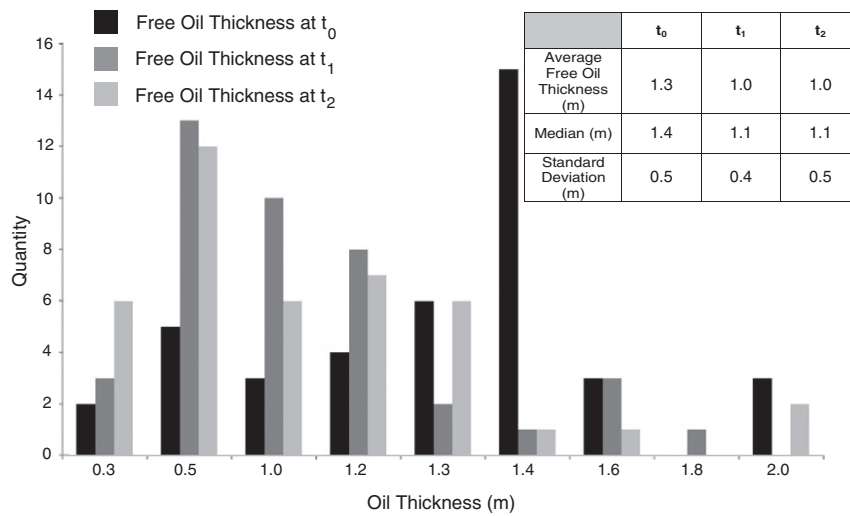


Figure 10. Oil thickness in the wells before, 6 months after, and 18 months after start of remediation.

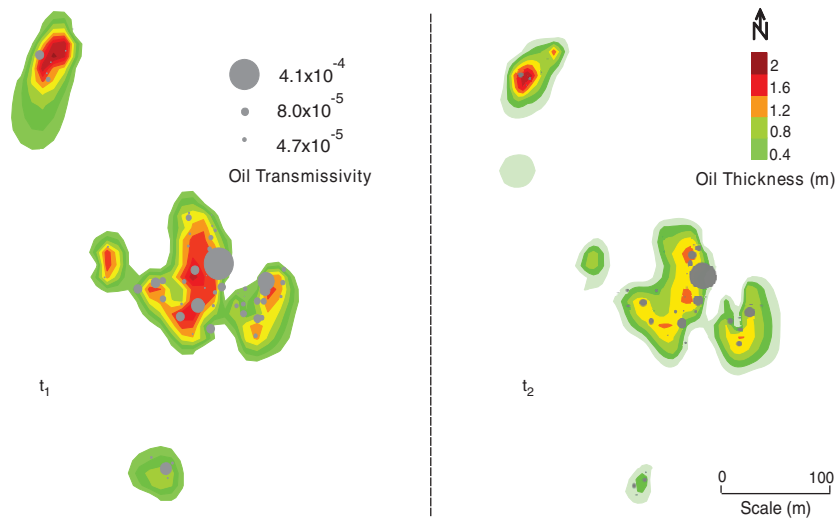


Figure 11. Oil thickness in wells (at t_0 and t_2) and T_0 values distribution (at t_0 and t_2).

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 120cP) 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 transmis-

sivity 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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Appendix C

Oil saturation results - PZ260

Table C.1: Measured Oil Content - PZ260

Core Number	Depth (mbgl)	Oil (mg/kg)
PZ260-1	2.1	84
PZ260-2	2.3	150
PZ260-3	2.5	254
PZ260-4	2.7	105
PZ260-5	2.9	10
PZ260-6	3.5	14446
PZ260-7	4.1	117530
PZ260-8	4.3	126275
PZ260-9	4.5	50000
PZ260-10	4.7	2813
PZ260-11	4.9	144

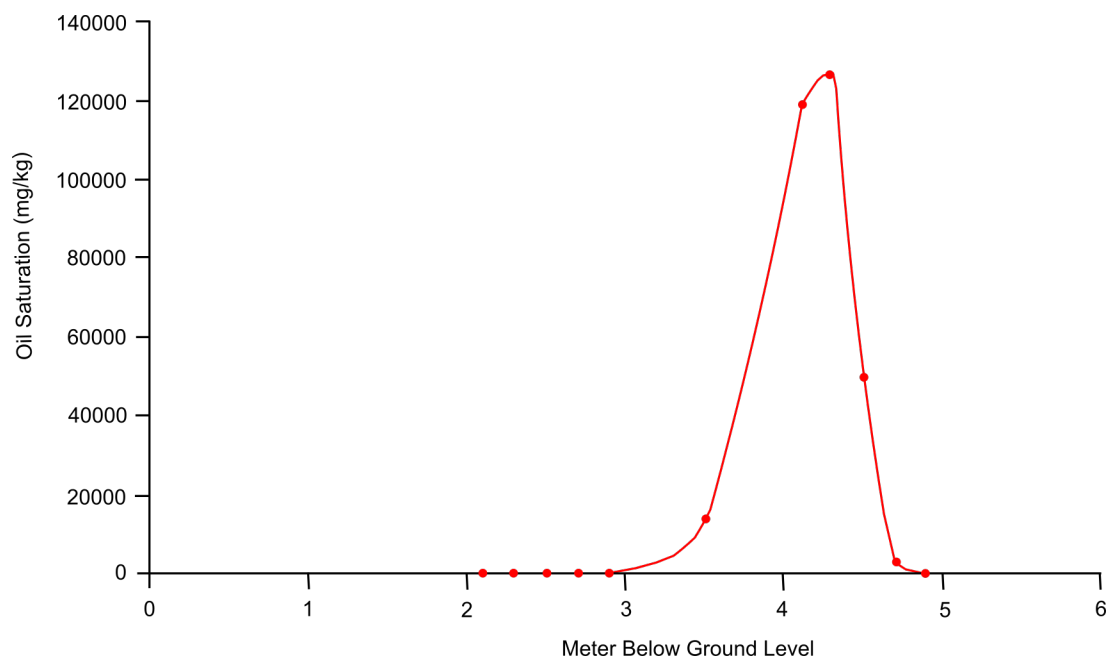


Figure C.1: Measured Oil Saturation at depth - PZ260

Appendix D

Interfaces levels and oil thickness - Unconfined oil layer

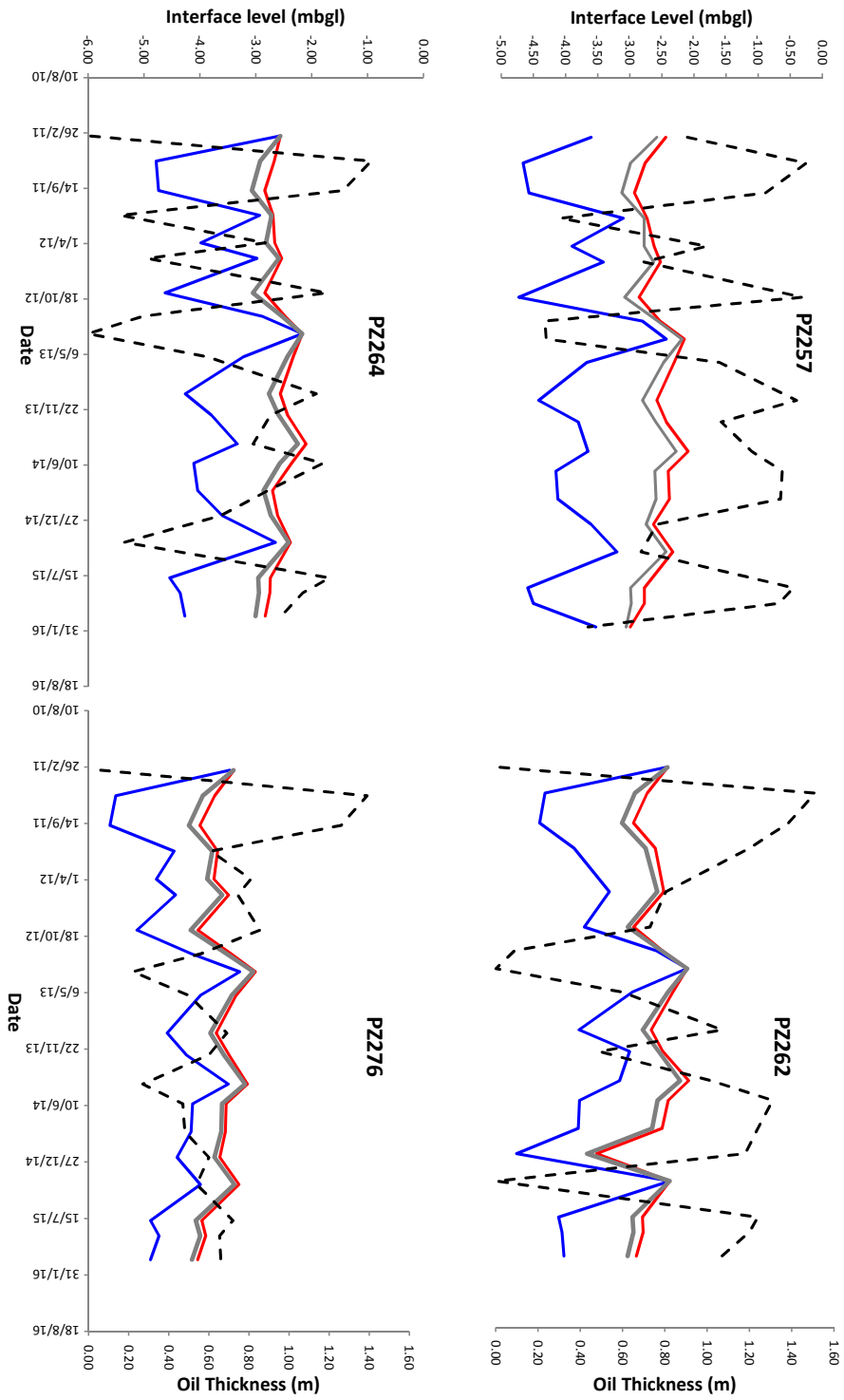


Figure D.1: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve) and oil thickness in the wells (black dotted line curve)

Appendix E

Oil/water interface versus oil thickness curves - Unconfined oil layer

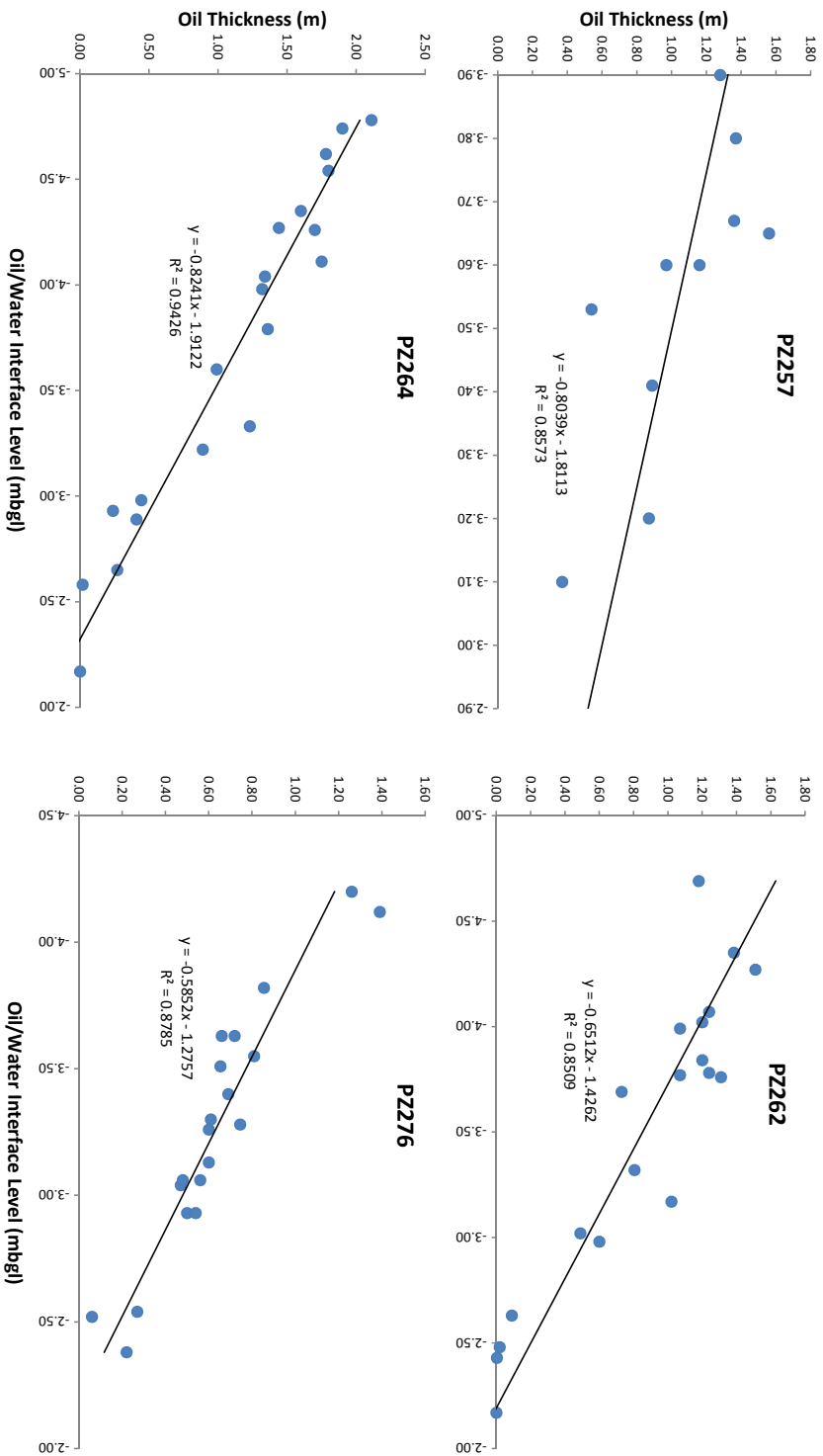


Figure E.1: Oil/water interface level versus measured oil thickness in the monitoring wells

Appendix F

Interfaces levels and oil thickness - Confined oil layer

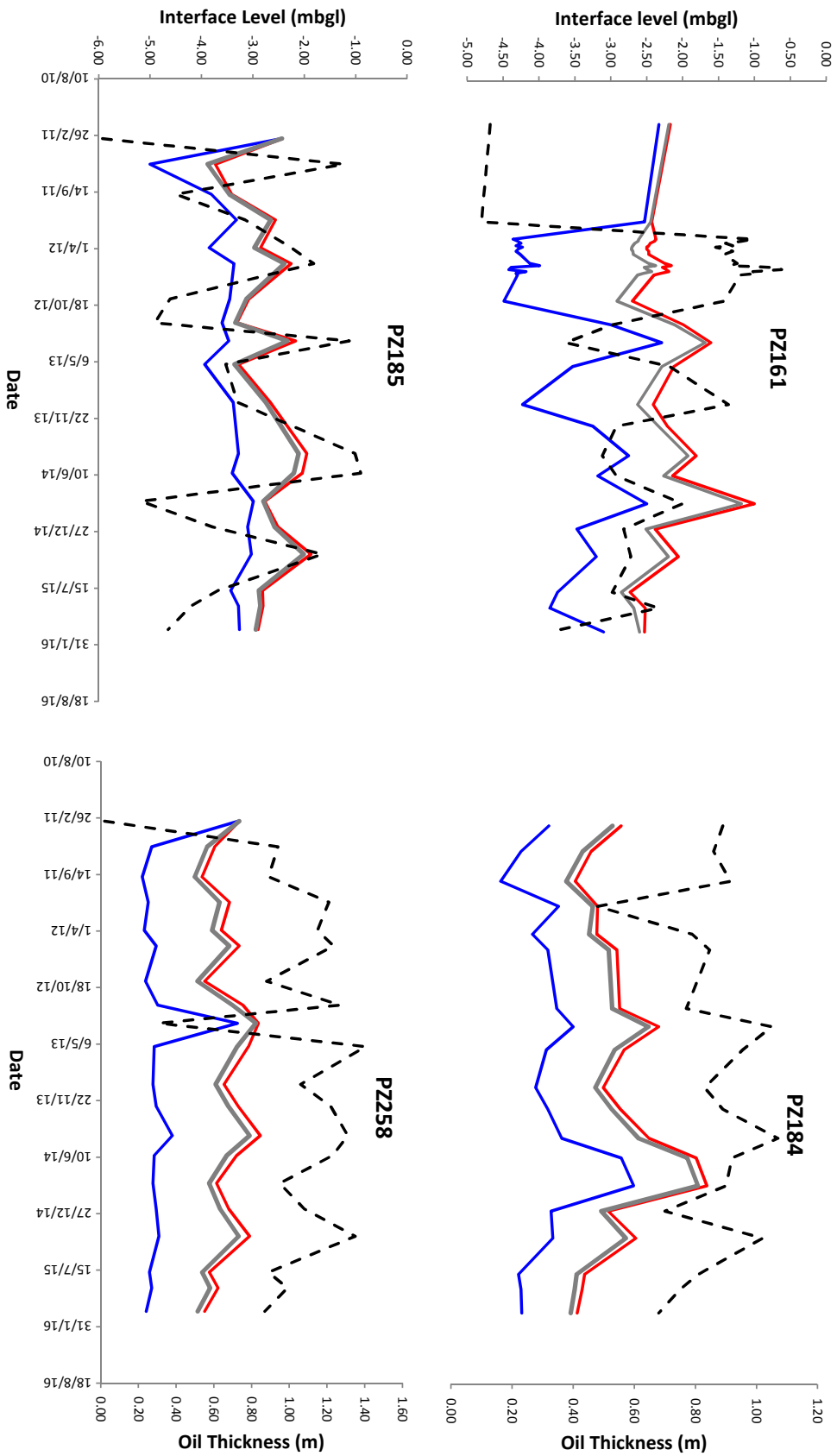


Figure F.1: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve) and oil thickness in the wells (black dotted line curve)

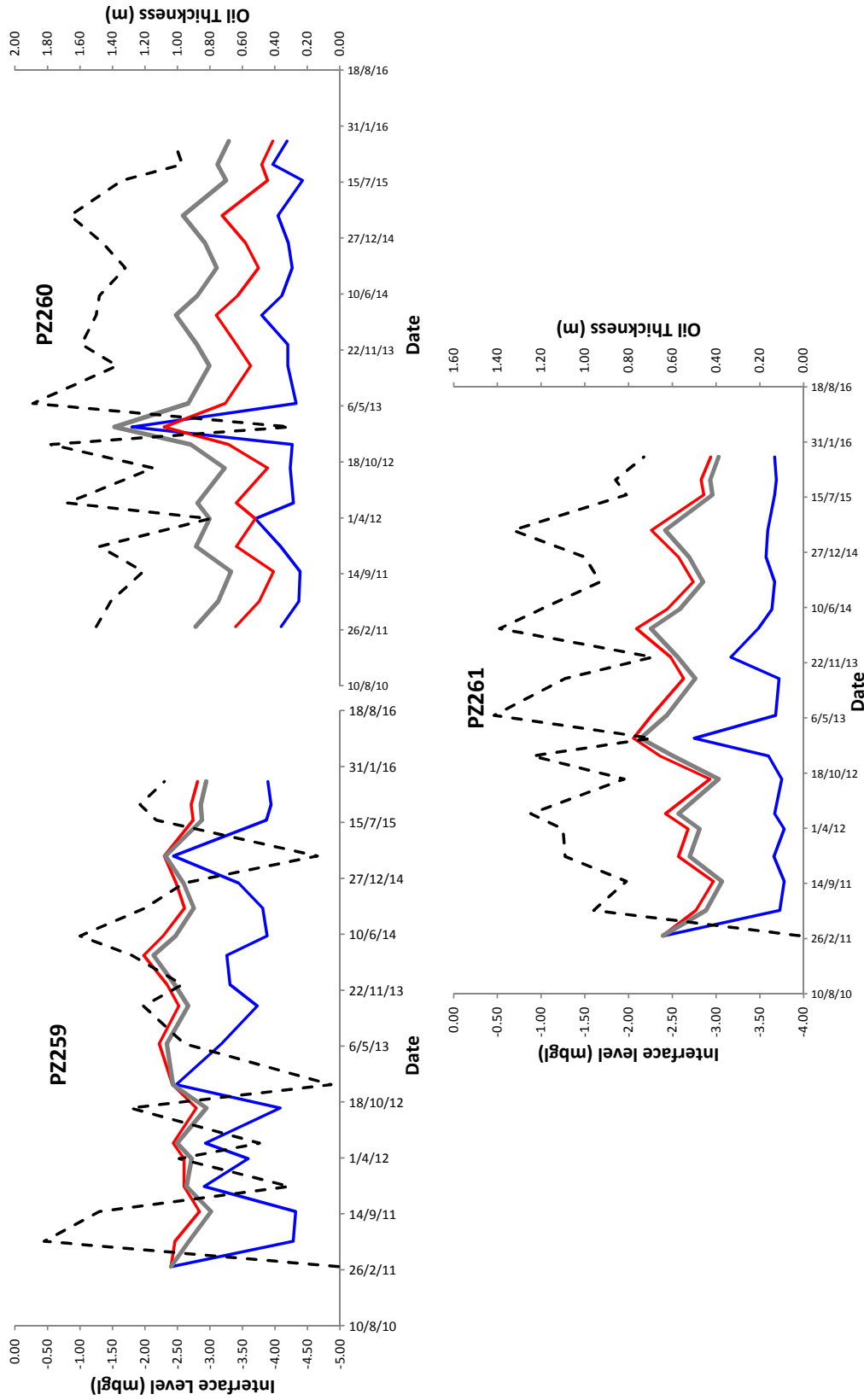


Figure F.2: Oil/water interface level (blue curve), oil/air interface level (red curve), total potentiometric surface (grey curve) and oil thickness in the wells (black dotted line curve)

Appendix G

Oil/water interface versus oil thickness - Confined oil layer

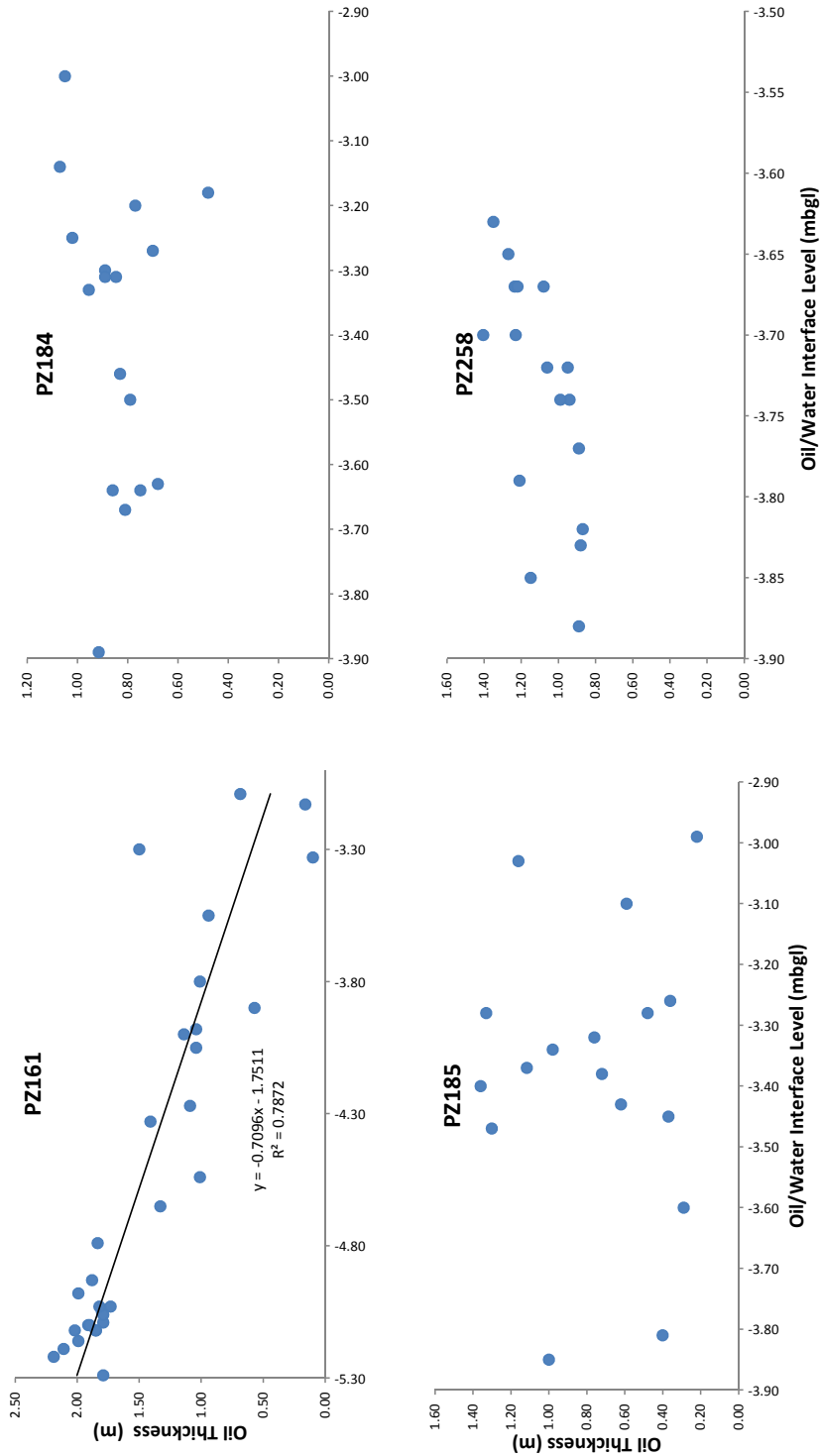


Figure G.1: Oil/water interface level versus measured oil thickness in the monitoring wells

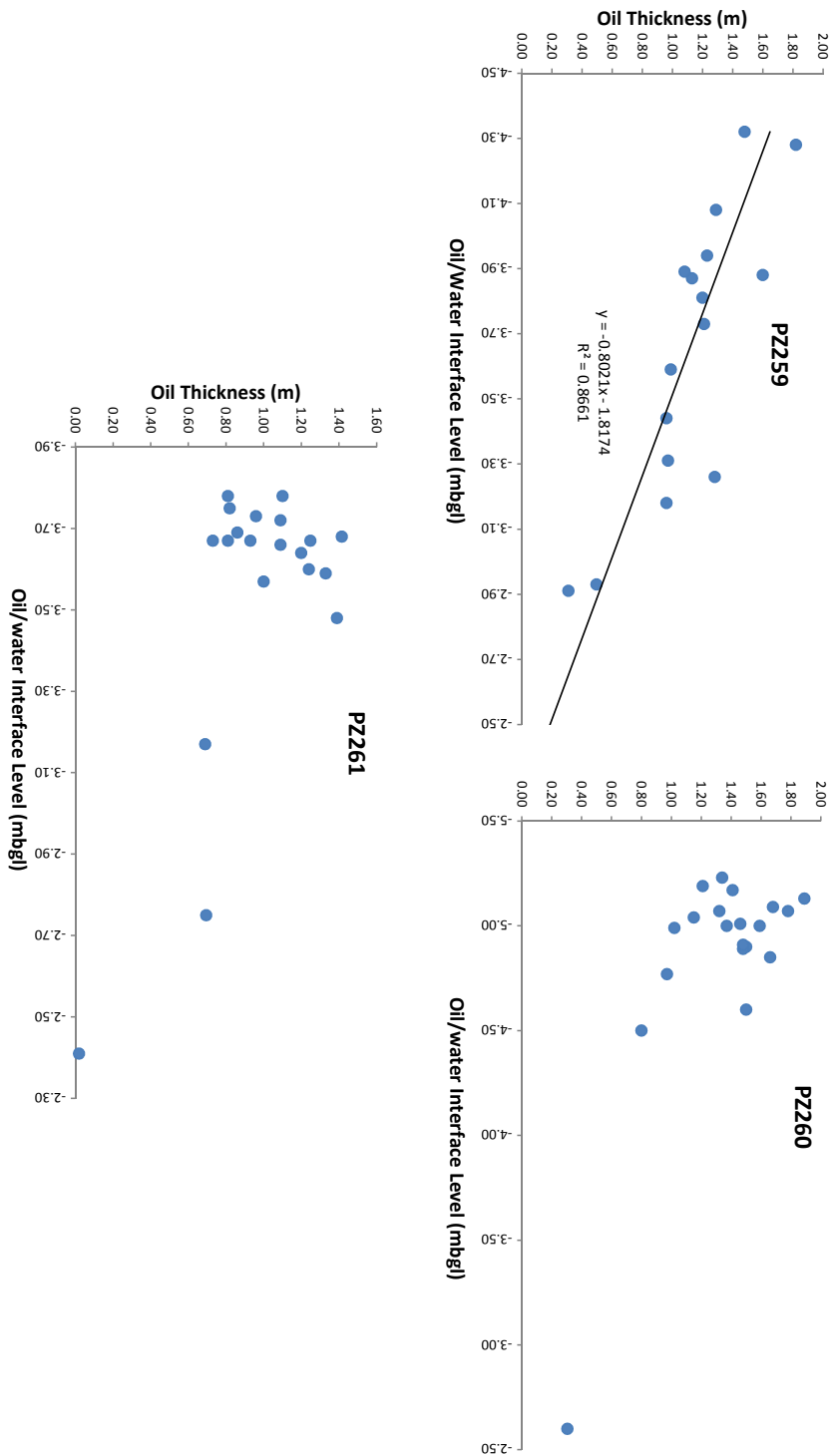


Figure G.2: Oil/water interface level versus measured oil thickness in the monitoring wells

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