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# **Imaging the hydraulic properties of a contaminated alluvial aquifer perturbed with periodic signals**

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**Conflict of interest:** None

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## 1   **Abstract**

2   Imaging characterization of a heterogeneous alluvial aquifer at a decametric scale is presented.  
3   The characterization relies on responses to oscillatory pumping tests led in two different wells  
4   and at two different periods of oscillation (5 and 10 min). These specific oscillatory responses  
5   are extracted from the hydraulic pressure values, measured in 13 boreholes during the pumping  
6   tests, through a data processing procedure. Then, a deterministic inversion process, led with a  
7   two-dimensional hydraulic properties model, aims to reproduce this set of oscillatory responses,  
8   in a frequency domain, by optimizing the distribution of the property values in the model. Two  
9   inversion processes are led separately with each set of responses corresponding to the two  
10   periods of oscillation used, and one joint inversion is led with the set of all responses together.  
11   The inversion results image the heterogeneities in the distribution of the field properties. The  
12   results suggest that longer periods of oscillation (in this case 10 min) permit characterization of  
13   larger areas around the pumping wells. In contrast, shorter periods (in this case 5 min) propagate  
14   more readily in the conductive zones near the pump and provide less information for the less  
15   conductive areas. Therefore, it appeared that performing a joint inversion, combining the  
16   information carried by the responses to both periods, provided more information on the  
17   heterogeneous distribution of the field properties and resulted in better constrained property  
18   maps than the ones obtained from separate inversions.

## 1. Introduction

The assessment of subsurface hydraulic properties at field scale is a critical step for the selection and the implementation of an effective remediation protocol for contaminated aquifers. Generally, estimates of these properties (mainly transmissivity and storativity) are obtained from the analysis of measured hydraulic signals in response to extraction of water from a pumping well (Butler 2005; Batu 1998; Neuman and Witherspoon 1972; Le Borgne et al. 2004; Li et al. 2008; Wen et al. 2010). The interpretation of pumping tests can be made with an analytical model of the groundwater flow equation, with the assumption of homogeneity, to deduce averaged values of these properties (Sanchez-Vila et al. 1999), or by using hydraulic tomography to determine their spatial heterogeneity (Yeh and Lee 2007). Hydraulic tomography has been widely explored during the last few decades to identify hydraulic features of aquifers with various hydrogeological conditions (Yeh and Liu 2000; Zhu and Yeh 2005; Bohling et al. 2007; Illman et al. 2009; Cardiff et al. 2009; Berg and Illman 2015; Fischer et al. 2017). The approach is mainly based on the implementation of an optimization code to find the spatial distribution of the hydraulic properties able to reconstruct all recordings of hydraulic data collected during the pumping tests.

Illman et al. (2010) show and underline the fact that an accurate spatial imaging of the hydraulic properties is key to a better prediction of the contaminant transport in heterogeneous contaminated aquifers. These predictions represent the basis for the design of protocols of remediation for polluted sites. Therefore, characterizing the hydraulic properties in a contaminated field site represents a specific research problem discussed in several recent articles (Wagner 1992; Rasmussen et al. 2003; Berg and Illman 2013; Hochstetler et al. 2016). However, use of the traditional pumping test requires an extraction of large water volumes in order to generate measurable drawdowns, and this procedure results in additional costs for treating or storing these quantities of polluted water.

Rasmussen et al. (2003) thereby elaborated a pumping-injection system, in which the pumped water is stored in a tank, before being reinjected into the aquifer. This system generates an oscillatory solicitation signal, with pumping rates oscillating between positive and negative extrema, which induces oscillation in the groundwater pressure. Such oscillation of pressure can also be generated without pumping, by movement of mass at the air-water interface in a well (Guiltinan and Becker, 2015).

Making use of oscillatory rates, instead of constant rates, during the pumping tests, for the characterization of the distribution of field properties, has attracted significant attention (Lavenue and de Marsily 2001; Cardiff et al. 2013; Rabinovich et al. 2015; Zhou et al. 2016; D'Oria et al. 2018). These oscillatory rates generate oscillatory responses over the hydraulic level. A guideline has been proposed by Cardiff and Barrash (2015) for the implementation of oscillatory pumping tests at field scale. The oscillatory responses can be easily extracted from the other responses and noises in the measurements (Bakhos et al. 2014; Cardiff and Slayer 2016). Then, the amplitude decay and phase shift of the signal between a measurement point and the pumping point permit assessment of information on the subsurface properties.

The efficiency of such signals has already been exploited to create an image of the property distribution in a heterogeneous medium (Zhou et al. 2016, Cardiff et al. 2019), to estimate the hydraulic connectivity between wells at a fractured site (Guiltinan and Becker 2015), to image a conduit network in a karstic aquifer (Fischer et al. 2018), to detect leakage from a subsurface formation (Sun et al. 2015), or to localize non-aqueous phase liquid (NAPL) sources and monitor their spreading (Zhou and Cardiff 2017).

This work aims to quantitatively characterize, at a decametric scale, the subsurface properties of a contaminated heterogeneous alluvial aquifer that is hydraulically influenced by a natural tidal signal, complicating extraction of the observed response. Furthermore, as the site is contaminated, the volume of water to be extracted for the characterization has to be limited.

Therefore, oscillatory pumping rates appear as an interesting alternative, thereby avoiding problems caused by these two issues at the same time. Thus, two oscillatory pumping tests (led with two different periods of oscillations) were performed at the study site, and the responses were used with a deterministic inversion process to interpret the distributions of transmissivity, storativity and diffusivity over the field site. Inversion processes are led separately with each set of responses corresponding to both periods of oscillation used (5 min and 10 min), and also jointly using both sets of responses together. The different interpretations made from these different inversions will provide information, brought about by the responses to different periods of oscillations at this scale.

The article begins with a presentation of the study site, the oscillatory pumping tests and the data processing approach. Then, the modeling method and the inverse problem are detailed. In the last section the results of the hydraulic imaging are provided and there is a discussion concerning the choices involved in using oscillatory responses.

## **2. Site and data presentation**

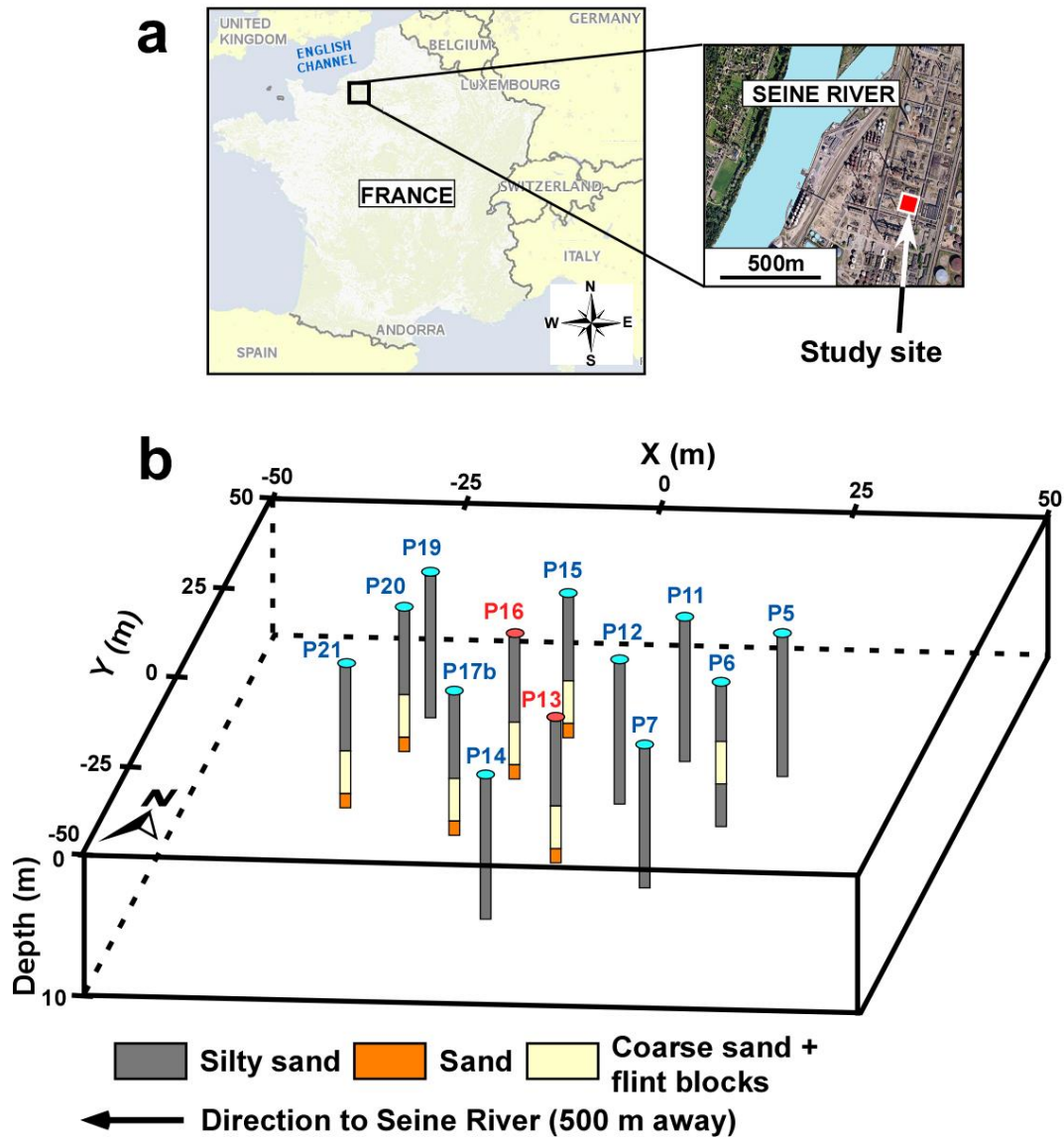
### **2.1. Study site**

This work investigates the subsurface under a former petroleum refinery located near the town of Rouen (Normandy), in the North West of France. The buildings of the refinery have been demolished and the field site is actually in a depollution stage. The studied site corresponds to a 100 m  $\times$  100 m parcel of the overall field site (see Figure 1). The subsurface of the study site is composed of 10-m depth of a heterogeneous deposit (silty sands, coarse sands and chalk/flint blocks) lying on a chalk horizon.

The investigated aquifer is limited to this heterogeneous superficial medium, wherein complex flows are occurring. In order to understand the heterogeneity of this aquifer, the site is equipped with 21 boreholes, drilled through the whole aquifer unit. The boreholes are made of HDPE

93 with a diameter of 163 mm and are screened from 3 m to 10 m depth. The geological logs of  
94 these boreholes indicate that some wells intersect only silty sands over the 10-m thickness of  
95 the aquifer, while some others intersect the same silty sand unit in the first 6 m and then a more  
96 permeable unit composed of coarse sands and flint blocks from 6 m to 9 m depth (Figure 1).  
97 From the logs of excavations on the wider site (near to the investigated area and showing the  
98 same geological successions) and a previous hydrogeophysical study of this field site (De  
99 Clercq et al., 2020), it was observed that this flint/chalk block unit can include very conductive  
100 flow paths, and thus generate localized, but important, flow velocities within the site. Therefore  
101 it is expected that the property distribution in this field site is highly contrasted, as this very  
102 conductive unit is not spatially continuous.

103



104

105 Figure 1: a. Location of the study site in France and b. Map of location of the existing boreholes  
 106 (circles) on the study site. Boreholes indicated with red circles represent the pumping wells and  
 107 boreholes indicated with blue circles represent the measurement wells. The geological log of  
 108 each borehole, from surface to 10-m depth, is shown on the map as a colored column.

109

110 The superficial aquifer is considered as semi-confined under the silty sands. The static water  
 111 level in the aquifer is mainly influenced by the sea tidal signal of the Seine River located 500  
 112 m on the west side of the study area. Floating light non-aqueous phase liquid (LNAPL) was  
 113 measured with a SOLINST interface meter before pumping; two wells had significant LNAPL-



layer thickness prior to pumping: P19 (60 cm, i.e. 12% of the groundwater column) and P16 (120 cm, i.e. 24% of the groundwater column). No floating LNAPL was present in a significant quantity in the other monitored wells of the study site during the pumping investigation.

The floating NAPL was regularly measured in each well of the field site between 2016 and 2019. Thus, frequencies of occurrence of floating NAPL have been measured with the 30 measurements performed, in each well, during this period. It is believed that this floating NAPL is more likely to be entrapped in less diffusive areas of the site. Therefore, these frequencies of occurrence were used to eventually assess the modeled spatial distribution of hydraulic diffusivity.

## 2.2. Piezometric responses to the pumping signals

Two different pumping tests were conducted in P13 and P16, each time for two different periods of oscillation of the pumping signal (5 min and 10 min). The oscillation signal was generated around a constant mean pumping signal, so that the pumps were constantly pumping, at varying rates, during the investigation. The oscillating rates were generated and piloted by an automated device, based on an electric variator, connected to the pump. This device was modified internally, as such devices are not produced for sale currently, and has been designed to control any type of pump. The different pumping tests were conducted, for each period of oscillation, long enough to produce 6 to 7 oscillations (total duration of 1 h maximum for the period of 10 min). The temporal evolution of the pumping rate of these tests is given by:

$$Q(t) = Q_{\text{mean}} - Q_{\text{amp}} \cdot \cos(\omega t) \quad (1)$$

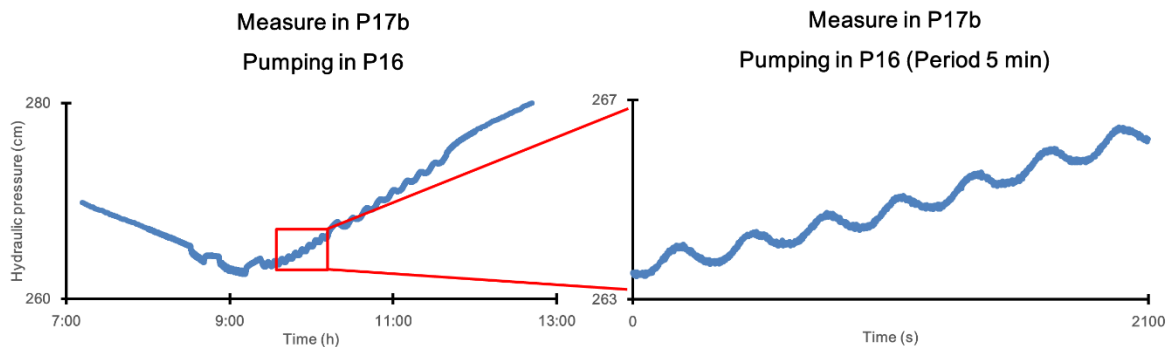
where  $Q$  is the pumping rate ( $\text{m}^3/\text{s}$ ),  $Q_{\text{mean}}$  is the pumping constant mean signal ( $\text{m}^3/\text{s}$ ),  $Q_{\text{amp}}$  is the pumping constant amplitude of oscillation ( $\text{m}^3/\text{s}$ ) and  $\omega$  is the angular frequency ( $\text{rad/s}$ ) also equal to  $\frac{2\pi}{P}$  where  $P$  is the period (s).

The harmonic pumping tests were led with  $Q_{\text{mean}} = 8.8 \text{ L/s}$  and  $Q_{\text{amp}} = 3.7 \text{ L/s}$  in P13, and with  $Q_{\text{mean}} = 9.7 \text{ L/s}$  and  $Q_{\text{amp}} = 4 \text{ L/s}$  in P16.

During these two pumping tests, the hydraulic level variations in 13 boreholes (including the two pumping boreholes) were continuously measured, in terms of pressure, with CTD Diver probes with an accuracy of  $\pm 0.05 \text{ \%FS}$  (%FullScale).

### 2.3. Data processing

Figure 2 presents an example of hydraulic pressure measured in one well during the pumping test in P16. Data processing on the hydraulic level measurements needs to be realized in order to extract the specific oscillatory responses, in the different wells, to the oscillation induced by the pumping. These specific responses will be described in terms of amplitude and phase offset (relative to the pumping signal).

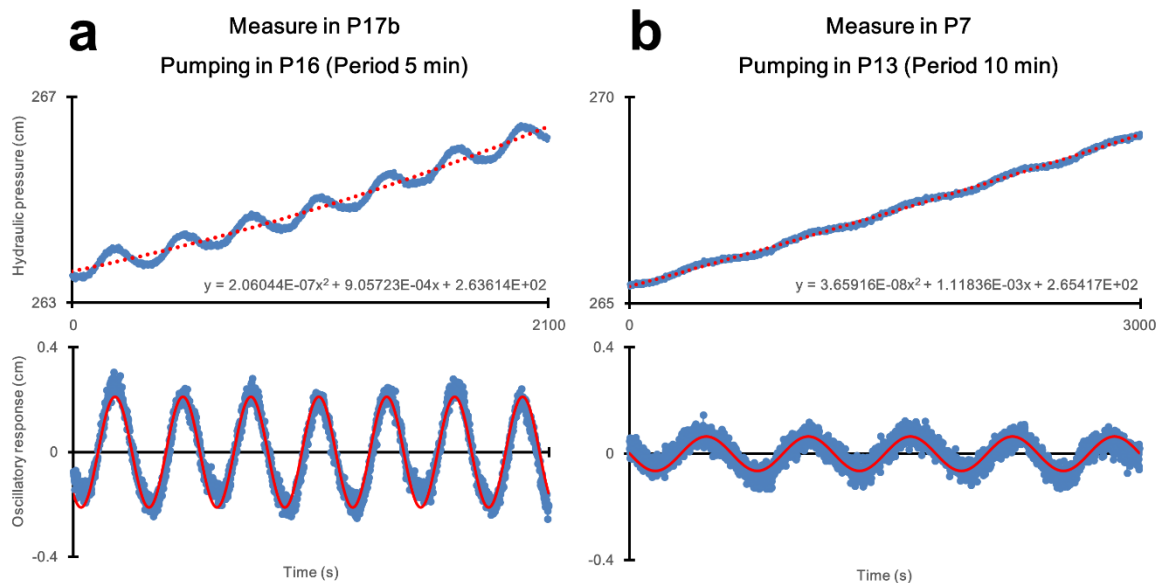


**Figure 2:** Graphs of the responses measured in P17b (during a pumping in P16) superposed on the tidal signal induced by the nearby Seine River. The left graph represents the responses measured during the entire pumping test in P16, while the right graph represents a zoom on the responses to the period of oscillation 5 min.

First, the global trend, mainly controlled by the Seine tidal signal is removed from the raw measurements, as presented in the two examples in Figure 3. At the time scale of the pumping

tests (max. 1 hour) the global trend can be assimilated to a second-order polynomial, adjusted to the measured data, which is then subtracted from the raw measurements. After this operation, only the noisy oscillatory responses to the oscillations of the pumping tests remain.

The second process consists of a Fast Fourier Transform (FFT) on the oscillatory responses in order to denoise the signal and interpret each oscillatory response in terms of amplitude and phase offset values, which are timeless and can be used in the oncoming frequency domain modeling. The FFT is performed in MATLAB with the FFT function which returns complex numbers used to calculate the amplitude and phase for each frequency of oscillation contained in the signal. It was then verified that, for each FFT performed, the interpreted oscillation was coherent with the measurement.



**Figure 3:** Graphs of the responses measured in **a** P17b (during a pumping in P16) and **b** P7 (during a pumping in P13) as examples of the data processing performed on each measured response. The global trend is subtracted from the hydraulic pressure (this trend is approached with a quadratic equation as shown with the dotted red lines) to isolate the oscillatory response in each measurement. Then a FFT is performed on these oscillatory responses to interpret their amplitudes and phase offsets as purely sinusoidal signals (red lines).

Once the data processing has been performed for each measured well, a map of amplitude and phase offset responses can be produced (Figure 4). The amplitude and phase responses appear to be correlated: globally, a low amplitude response is associated to a high phase offset. Therefore, the amplitude of the signal is decaying when propagating away from the pumping well, while its phase offset increases. These amplitude and phase responses are related to the heterogeneity of the hydraulic properties of the aquifer. Thus, their distribution allows one to describe, qualitatively or quantitatively, the heterogeneity of the field site.

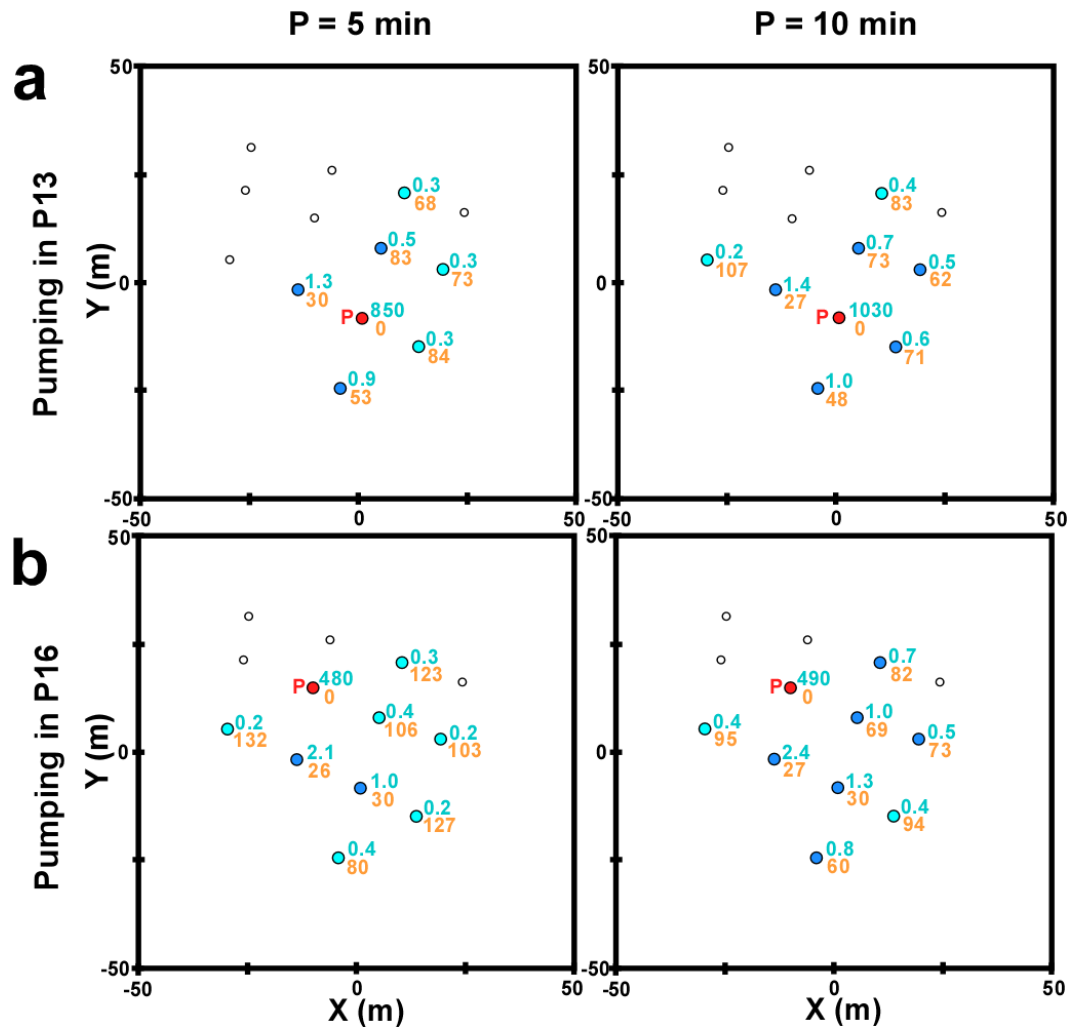


Figure 4: Maps of the amplitudes (in blue, in mm) and phase offsets (in orange, in  $^{\circ}$ ) interpreted for each measurement point: **a** pumping in P13, **b** pumping in P16. The maps are presented for the two pumping wells (designated as a red 'P') and for the two periods of pumping signal ( $P = 5, 10$  min.). Uncaptioned boreholes represent an absence of oscillatory response in the measurement (amplitude < 0.1 mm).

These maps permit visualization of the spatial evolution of the oscillatory responses for each pumping well when the period of solicitation signal is modified. The heterogeneity of the study site can already be perceived here, as the influence of each pumping does not propagate circularly. In fact, the areas impacted by the pumping tests show particular directions of propagations of the oscillatory signal. For example, for a pumping in P16 for the period 5 min, the signal propagates mainly to the south and only with lower responses to the boreholes to the east. This may highlight a preferential path of propagation southward from P16. However, for the period 10 min, the responses remain localized to the south and east of the pumping location but show more homogeneous responses in these two directions.

These oscillatory responses can be associated to an inversion process in order to quantitatively characterize the heterogeneity and to estimate the spatial distribution of the properties over the study site. It is then possible to check if the modeled property distributions can be correlated to the known geology of the field site and the measured pollution appearance (frequency of occurrence of floating NAPL), in order to better understand the propagation of the pollutants throughout the site.

### **3. Modeling strategy**

#### **3.1. Forward problem and model parameterization**

For the modeling part, the aquifer and the flows are considered to be two-dimensional (2D; top-down view). In fact, geologically, the main spatial variation is generated by the existence of localized deposits of flint and chalk blocks, which are always intersected at the same depths (6 m to 9 m) by some boreholes. Furthermore the groundwater flows generated by the pumping tests induced generally horizontal streams. In fact, the most important drawdowns (30 cm to 1 m), which are associated to vertical flows, were localized only at the pumping wells, whereas,

over the rest of the field site, the drawdowns were of an order to magnitude of millimeters (see Figure 4).

The 2D forward problem, hereafter noted  $f$ , in the frequency domain, permits one to simulate the spatial amplitude and phase offset responses to a pumping signal from property values distributed over the plan model and from the following equation of flow continuity (associated to Darcy's law) (Cardiff et al. 2013):

$$i \omega S_s H_\omega - \nabla \cdot (K \cdot \nabla H_\omega) = \frac{Q_{\text{amp}}}{V_{\text{el}}} \delta(x - x_q, y - y_q) \quad (2)$$

where  $S_s$  is the specific storage (1/m),  $K$  is the conductivity (m/s),  $H_\omega$  is a complex parameter holding the spatial amplitude and phase offset responses in the frequency domain,  $i$  is the imaginary unit,  $Q_{\text{amp}}$  is the amplitude of oscillation in the rate of a harmonic pumping ( $\text{m}^3/\text{s}$ ) led at a coordinate  $(x_q, y_q)$ ,  $\delta$  is the Dirac distribution and  $V_{\text{el}}$  is an elementary volume from the finite element mesh of the model associated to the pumping locations.

One considers  $H_\omega(x, y) = 0$  at the boundaries of the model as the boundary condition and all over the model as the initial condition. In order to reduce the effect of the boundary conditions on the simulations in the field area, it was necessary to enclose the area of interest in the model in a larger buffer zone ( $500 \times 500 \text{ m}^2$ ) associated with uniform regional hydraulic properties, thus moving the boundaries away from the areas impacted by the pumping tests in the models. In this work, Equation (2) was solved on a triangular finite element mesh with COMSOL Multiphysics. The meshing is adaptive, which means that it is refined automatically around the borehole locations in the model. The mesh in the model is composed of 26,616 triangular elements.

235 The amplitude and phase offset responses over the model can then be extracted from the  
 236 complex parameter  $H_\omega$  as follows:

$$237 \quad A(x, y) = \sqrt{(\operatorname{Re} H_\omega(x, y))^2 + (\operatorname{Im} H_\omega(x, y))^2} \quad (3)$$

238 with  $A$  the amplitude response (m), and  $\operatorname{Re}$  and  $\operatorname{Im}$  the functions returning respectively the real  
 239 part and the imaginary part of  $H_\omega$ .

$$240 \quad \Phi(x, y) = \frac{180}{\pi} \operatorname{atan2}(-\operatorname{Im} H_\omega(x, y), \operatorname{Re} H_\omega(x, y)) \quad (4)$$

241 with  $\Phi$  the phase offset response ( $^\circ$ ) and  $\operatorname{atan2}$  the inverse tangent function with two arguments  
 242 (rad).

243 Here, the frequency domain permits performance of a timeless simulation of the oscillation  
 244 signals and saves a consequent amount of time compared to modeling in the time domain,  
 245 especially for the inversion.

### 246 **3.2. Inverse problem**

247 The inverse problem involves a forward problem in order to link the distribution of the property  
 248 values in the model (contained in a  $m$ -vector  $\mathbf{p}$ ) to the simulated amplitude and phase  
 249 responses (contained in a  $n$ -vector  $\mathbf{d}$ ):  $\mathbf{d} = f(\mathbf{p})$ . The forward problem is then seen as an  
 250 application  $f: \mathbb{R}^m \rightarrow \mathbb{R}^n$ . The aim of the inverse problem is to find a distribution of property  
 251 values which minimizes the difference between the measured and the simulated responses. This  
 252 goal can be achieved by minimizing the following objective function:

$$253 \quad \Psi = \frac{1}{2} (\mathbf{d}_{\text{obs}} - \mathbf{d})^T \cdot \mathbf{C}_d^{-1} \cdot (\mathbf{d}_{\text{obs}} - \mathbf{d}) + \frac{1}{2} (\mathbf{p}_{\text{prior}} - \mathbf{p})^T \cdot \mathbf{C}_p^{-1} \cdot (\mathbf{p}_{\text{prior}} - \mathbf{p}) \quad (5)$$

where  $\mathbf{p}$  and  $\mathbf{p}_{\text{prior}}$  are  $m$ -vector containing respectively the distribution of the property values (here transmissivity and storativity) over the model and their a priori values,  $\mathbf{d}_{\text{obs}}$  is a  $n$ -vector containing the measured responses and  $\mathbf{d}$  is a  $n$ -vector containing the responses simulated from the forward problem (here amplitudes and phases).  $\mathbf{C}_d$  is a  $(n \times n)$  covariance matrix on the data, including the uncertainties on the observed and simulated data, and  $\mathbf{C}_p$  is a  $(m \times m)$  covariance matrix on the property values.

In a deterministic inverse problem, the minimization of Equation (5) is performed iteratively, starting from an acceptable assumption of property values in  $\mathbf{p}$ . Then, for each iteration of the inversion, a sensitivity analysis of the distributed property values to the simulated data is operated by computing the Jacobian of the operator  $f$ :

$$\mathbf{J}_k(i, j) = \left. \frac{\partial f_i}{\partial \mathbf{p}_k} \right|_{\mathbf{p}_k(j) = \mathbf{p}_k(j) + \Delta p} \quad (6)$$

with  $\mathbf{J}_k$  the  $(n \times m)$  Jacobian matrix computed at an iteration  $k$  using a finite difference method and  $\Delta p$  is the finite difference step. It can be noted that the same sensitivity analysis can be also performed with an adjoint state approach, as described in Cardiff et al. (2013), which is generally less demanding in computation time.

The property values are then optimized, at an iteration  $k$ , from a linearization of the objective function:

$$\mathbf{p}_{k+1} = \mathbf{p}_k + \left( (\mathbf{J}_k)^T \cdot \mathbf{C}_d^{-1} \cdot \mathbf{J}_k + \mathbf{C}_p^{-1} \right)^{-1} \times \left( (\mathbf{J}_k)^T \cdot \mathbf{C}_d^{-1} \cdot (\mathbf{d}_{\text{obs}} - \mathbf{d}) + \mathbf{C}_p^{-1} \cdot (\mathbf{p}_{\text{prior}} - \mathbf{p}_k) \right) \quad (7)$$

At the end of each iteration the value of the objective function is recalculated and the iterative process continues until the inversion has reached a sufficient minimization of the objective function.



After the last iteration, the posterior variances on the different optimized values of properties can be estimated by computing the posterior covariance matrix:

$$\mathbf{C}_{p,post} = \left( \left( \mathbf{J}_{post} \right)^T \cdot \mathbf{C}_d^{-1} \cdot \mathbf{J}_{post} + \mathbf{C}_p^{-1} \right)^{-1} \quad (8)$$

where  $\mathbf{C}_{p,post}$  is the  $(m \times m)$  posterior covariance matrix and  $\mathbf{J}_{post}$  is the covariance matrix computed during the last iteration. The diagonal entries of this matrix hold the posterior variances associated to each property value in the model, thus allowing for the establishment of uncertainty maps on the inverted property values.

### 3.3. Inversion parameters

Two separate inversions have been led with the responses associated to the two different periods of pumping signals ( $P = 5$  and 10 minutes). This means that, for each separate inversion, both pumping test (P13 and P16) responses to one period of signal (5 or 10 min) are considered. Therefore, each separate inversion is led with a dataset of 26 couples of amplitude / phase-offset measured responses. Afterwards, a joint inversion, integrating the responses to the two periods of signals simultaneously, also for both pumping tests (P13 and P16), has been performed (with a dataset of 52 couples of amplitude / phase-offset measured responses).

The aim of these inversions was to image the 2D hydraulic properties of the study area ( $100 \times 100 \text{ m}^2$ ). Therefore 2D models of transmissivity ( $T$ ) and storativity ( $S$ ) were built, wherein the property values are distributed over a grid of  $m$  squared cells. In the inversion process, the property values were integrated in the form of  $\log_{10}$  values in  $\mathbf{p}$  and  $\mathbf{p}_{prior}$ , which allows for more stability.

The inversions were initialized with uniform models of properties ( $T = 10^{-3} \text{ m}^2/\text{s}$  and  $S = 10^{-3}$ ). The same property values were also kept as prior information in the inversion process and for the regional buffer zone. These means that property values were chosen accordingly to a global

site knowledge from pumping investigations at higher scale. Therefore, they represent a reasonable global estimate to begin the inversion and for the large-scale flows in the buffer zone.

For these inversions,  $\mathbf{C}_p$  and  $\mathbf{C}_d$  were considered as diagonal matrices, with  $\mathbf{C}_p = 0.1 \times \text{Id}(m)$  and  $\mathbf{C}_d = \sigma^2 \times \text{Id}(n)$  where  $\sigma = 0.1 \text{ mm}$  for the amplitude responses and  $\sigma = 5^\circ$  for the phase offset responses, and  $\text{Id}$  represents the identity matrix. It was decided not to integrate a variogram constraint on the distribution of the properties in the inversion, as it was foreseen that this distribution could be locally contrasted, which is incompatible with the smoothness brought by such constraint. In fact a variogram constraint would force a smooth distribution of the property values. However, the  $S$  values were constrained to remain within a range of  $10^{-1} < S < 10^{-5}$  in order to avoid unphysical values that could occur due to the absence of such geostatistical constraints in the inversion.  $\Delta p = 10^{-5}$  was taken for the Jacobian computation.

## 4. Results

### 4.1. Property maps

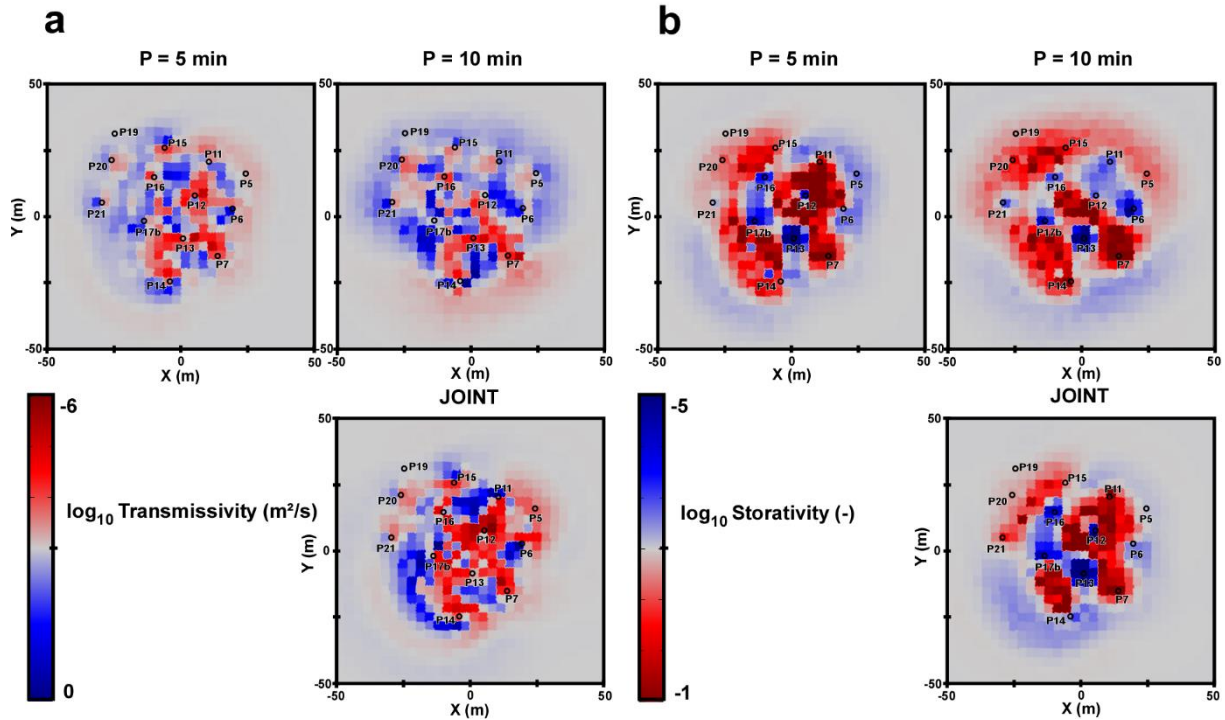
The results of the different inversions are presented in term of maps of distributed transmissivity and storativity values in Figure 5, in term of maps of diffusivity (calculated from the maps of transmissivity and storativity:  $D = \frac{T}{S}$ ) values in Figure 6, and in term of root mean square error (RMSE) between the measured and simulated amplitudes and phase-offsets in Table 1. Figure 7 also presents the maps of uncertainties on the inverted property values and the scatterplots obtained on the datasets after the inversions.

Each separately inverted model allows for a good reproduction of the amplitude responses (0.1 to 0.3 mm RMSE) and the phase-offset responses ( $1^\circ$  to  $3^\circ$  RMSE). The reproduction of the responses with amplitudes less than 1 mm appear to be less accurate (Figure 7). However, as

these responses approach the probe's measurement limits, they may be noisy and less relevant for an exact reproduction in the inversion. The result of the joint inversion presents a slight increase in the RMSE between the responses simulated with the model and the measurements, mostly on the amplitudes. It appears that this increase is mainly due to the responses from one borehole (P11 when pumping in P16) for which the amplitudes cannot be well reproduced for the two periods simultaneously. If one does not consider this borehole, the amplitude RMSE from the joint inversion becomes 0.3 mm. However the phases from these two boreholes remain well reproduced with the distribution in the joint inversion. Furthermore, an attempt was made at improving the amplitude reproduction in the joint inversion, which then resulted in a very bad misfit for the phase responses. Therefore, reproduction of the responses presents a globally satisfying compromise between amplitudes and phases, especially regarding the complexity of the study area.

**Table 1:** Results of the separate and joint inversions: size of the property cells in the grid and RMSEs on the amplitude (Amp. RMSE) and phase-offset (P.-O. RMSE) responses.

Inversion	Cell size	Amp. RMSE	P.-O. RMSE
$P = 5 \text{ min}$	$3.3 \times 3.3 \text{ m}^2$	0.2 mm	1 °
$P = 10 \text{ min}$	$3.3 \times 3.3 \text{ m}^2$	0.3 mm	3 °
Joint	$3.3 \times 3.3 \text{ m}^2$	0.6 mm	4 °



**Figure 5:** Maps of the distribution of **a** transmissivity and **b** storativity obtained with the separate inversions per period ( $P = 5, 10$  min.) of pumping signals and the joint inversion.

The property maps remain globally similar between the separate inversions and the joint inversion, showing a certain coherence of the datasets generated with different periods of oscillation. The  $T$  and  $S$  maps show very high heterogeneities within the field site, with important local variations and large ranges of values. This contrasted property distribution and the large range of values can be linked to the known geology and especially the observed high velocity flows that can exist within the coarse sands and flint blocks unit. Local transmissivity estimates from the joint inversion result were compared to measurements made at four locations (P6, P11, P14 and B4, a borehole located midway between P16 and P17b) by De Clercq et al. (2020) and are shown in Table 2. These estimates were made by integrating the inverted values in circles of 1-m diameter centered on the different locations. The inverted transmissivities are close to the measured ones. Except for P11, the transmissivity estimates appear as slightly underestimated.

The transmissivity fields present higher values on the west side of the area, lower values on the east side, and also decrease at the borehole locations, possibly indicating borehole effects on the flows. A similar degree of heterogeneity has been observed in the 3D conductivity field inverted from constant-rate pumping tests conducted on this site by De Clercq et al. (2020). In this 3D map, the heterogeneity is located mostly at the depths of the flint block unit, also suggesting that this unit may be responsible for the complex flows occurring on this site. Comparing these maps of transmissivity distribution to the conductivity model, they appear to be globally coherent, especially considering this study's result for a 10-min period, showing a more conductive path along P6 and P12. The conductivity model also suggests a continuous low-conductivity path from P14 to P21, to P20 and to P19, and a more conductive area than in this study's results around P7.

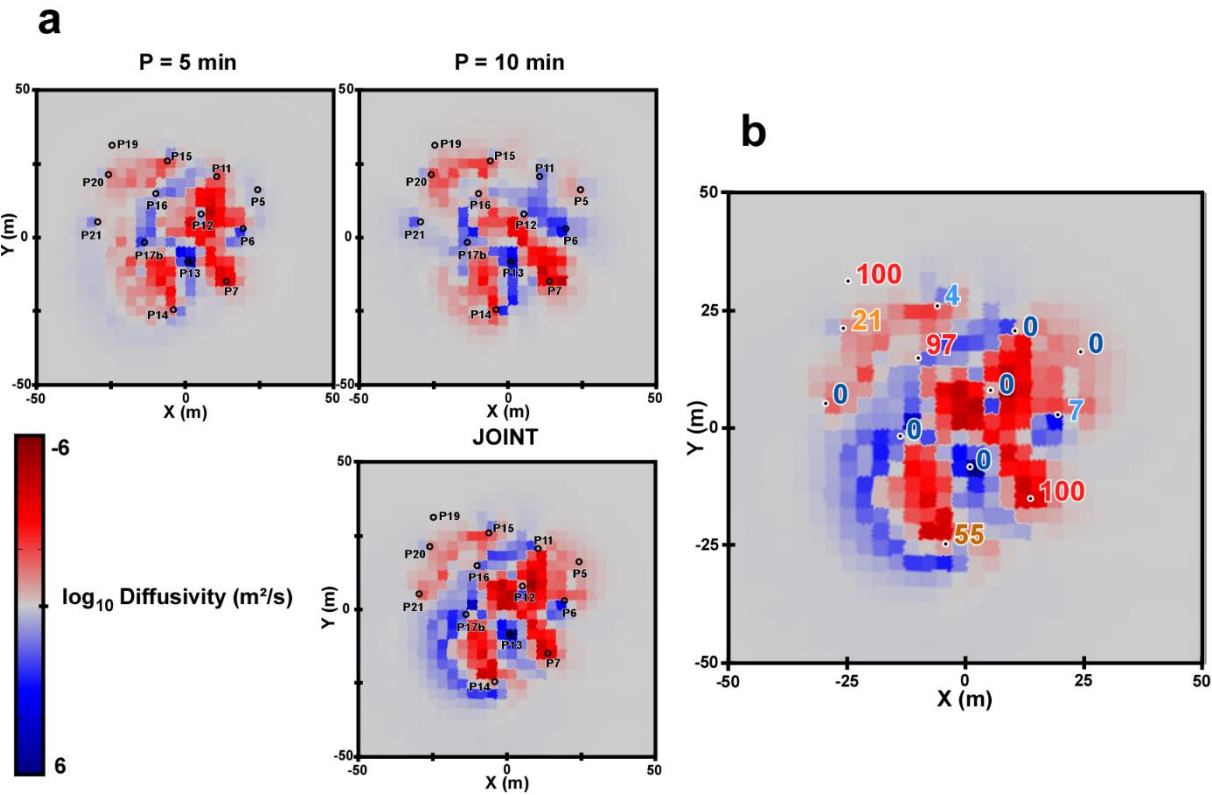
The highest values of storativity are grouped in three zones around P7, P14 and P15/P20/P19. In contrast, the lowest values of storativity seem to delineate a connectivity between P13, P17b, P16 and P15 for  $P=5$  min (and P21 and P6 for  $P=10$  min). These six boreholes are all located in the flint blocks unit (Figure 1), which might be continuous between them, and thus inducing a preferential flow connection. However, P20 is not associated with this connectivity in the model, whereas this borehole intersects the unit. This might be due to the fact that, if high flows can occur in this unit, they are not necessarily connected. The results obtained with the joint inversion indicate a less direct connectivity than suggested in  $P=10$  min between P16 and P6, but a higher connectivity in the direction of P21 than suggested in  $P=5$  min.

**Table 2:** Comparison between transmissivities measured at several locations (De Clercq et al. 2020) and transmissivities assessed from the joint inverted distribution.

Location	$\log_{10}(T)$ measured	$\log_{10}(T)$ inverted	Variation
P14	-3.70	-3.85	-0.15
P11	-3.01	-2.60	+0.41

P6	-2.93	-3.16	-0.23
B4 (between P16 and P17b)	-2.41	-2.76	-0.35

The coherence of the property distributions in the models can also be discussed by comparing the inverted maps of diffusivity (Figure 6) to the frequencies of occurrence of observed floating NAPL in each borehole of the field site.



**Figure 6:** **a** Maps of the distribution of diffusivity ( $T/S$ ) obtained with the separate inversions per period ( $P = 5, 10$  min.) of pumping signals and the joint inversion. **b** Map presenting, for each borehole, the value of frequency of occurrence of observed floating NAPL (in %), superposed on the diffusivity map obtained with the joint inversion.

The diffusivity maps (Figure 6) generated by the inversions with periods of oscillation of 5 and 10 min image a globally similar heterogeneity over the field site. A path of more important diffusivity appears along P13, P17b and P16. The responses to the period of signal 10 min

provide different information tending to indicate that this path continues beyond P16 and P17b, to P6 and P21. As for the S maps, this path seems to be geologically coherent as, in their logs, P13, P17b, P16, P21 and P6 intersect the unit of coarse sands and flint blocks.

The diffusivity map obtained with the joint inversion tends to reduce the importance of the diffusivity path toward P6 suggested in the result  $P=10$  min, while confirming the path toward P21 appearing on the same result. The diffusivity map can be linked to the values of frequency of occurrence of observed floating NAPL in each well (Figure 6). In fact, the wells in which floating NAPL is frequently observed are almost systematically associated to areas of low diffusivity in the model, except P15. In contrast, almost all wells in which no NAPL is observed are located on the continuous diffusive path imaged by the model, except P5. As the water table in this field site is constantly moving with the tide signal, it is believed that floating NAPL may be more likely entrapped in low-diffusivity areas.

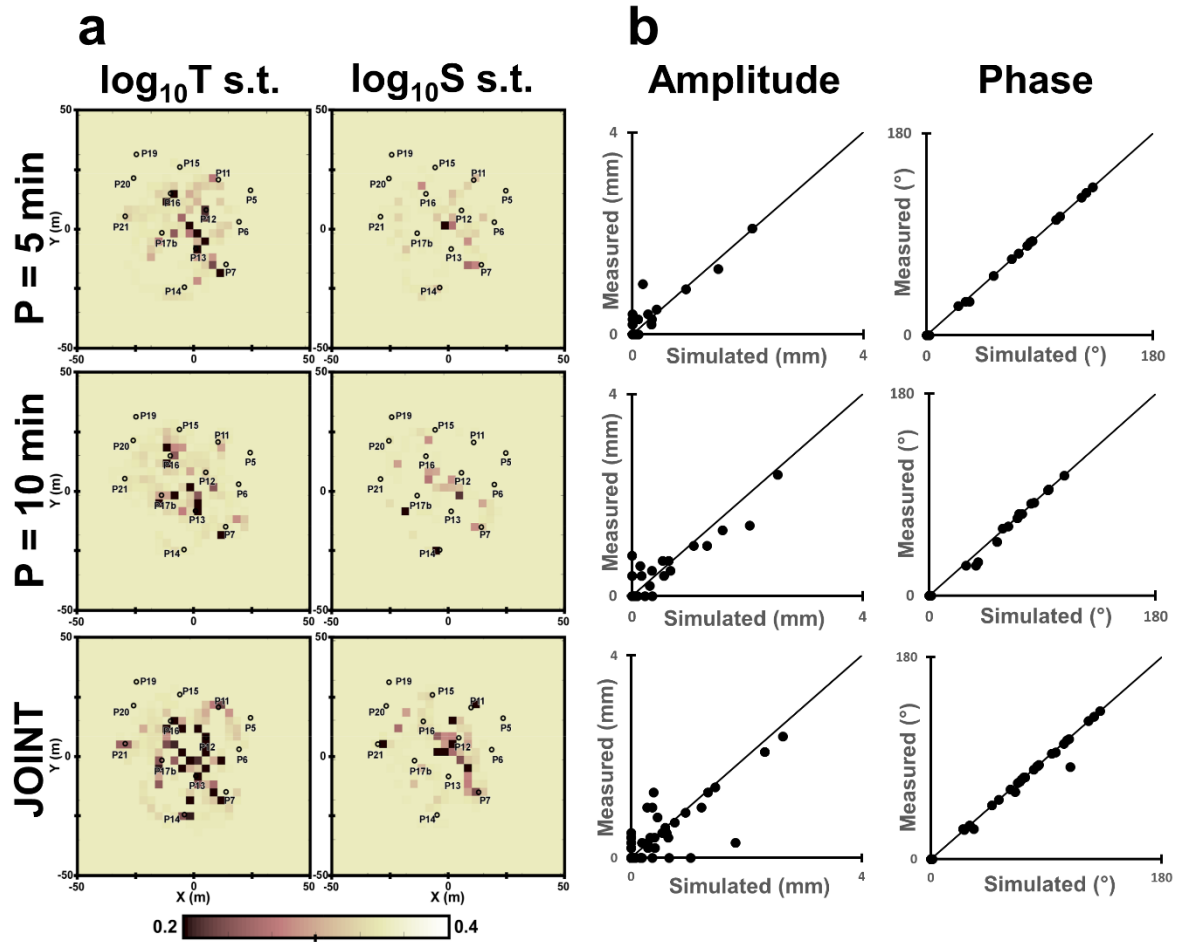


Figure 7: **a** Uncertainty maps (standard deviations on the  $T$  and  $S$  exponents) and **b** scatterplots of simulated vs. measured amplitudes and phases obtained for each separate inversion and the joint inversion.

The uncertainty maps in Figure 7 indicate that the joint inversion is better constrained than the two separate ones, showing that the responses to the two different periods of oscillation carry different information, as suggested in Cardiff et al. (2013). It is interesting to observe that the less uncertain areas in the  $T$  fields are located along the path of highest diffusivity in Figure 6, while the less uncertain areas in the  $S$  fields are more likely located in the zones of lowest diffusivity.

It was not possible to directly validate the values of  $T$  and  $S$  obtained in the inverted maps with field data. However, their similar distribution in the results of the separate and the joint

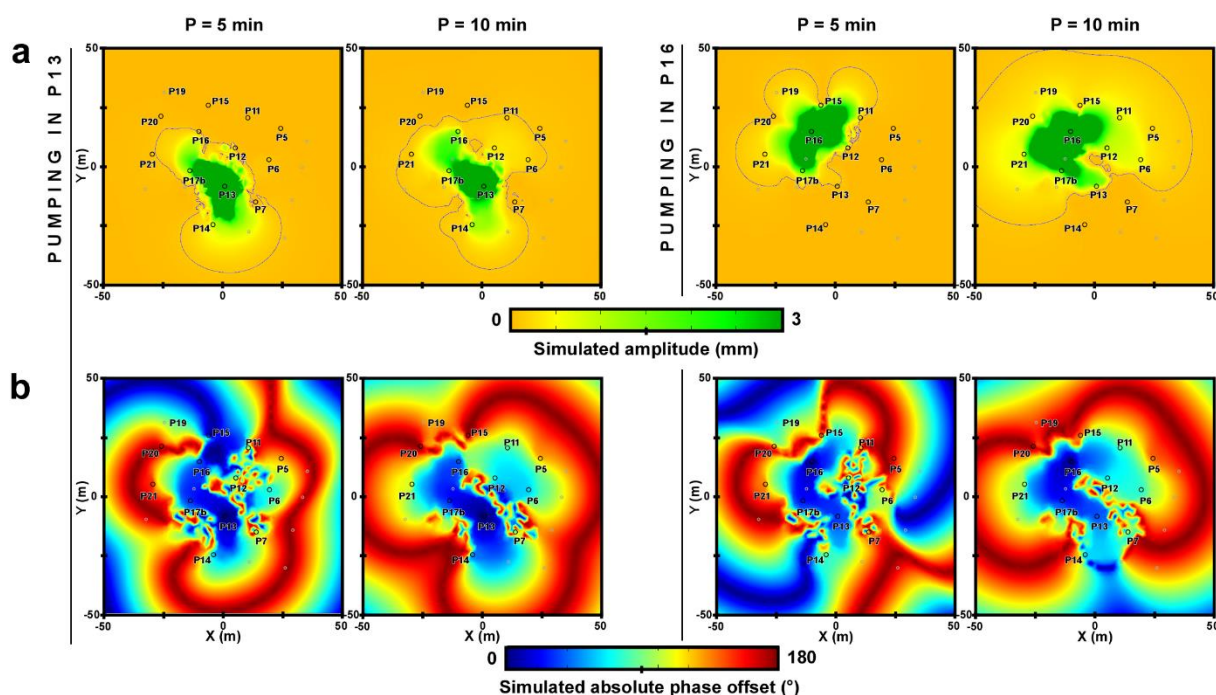


inversions appeared as coherent regarding the given knowledge on the geology of the field site and its behavior to contaminant mobility.

## 4.2. Simulations

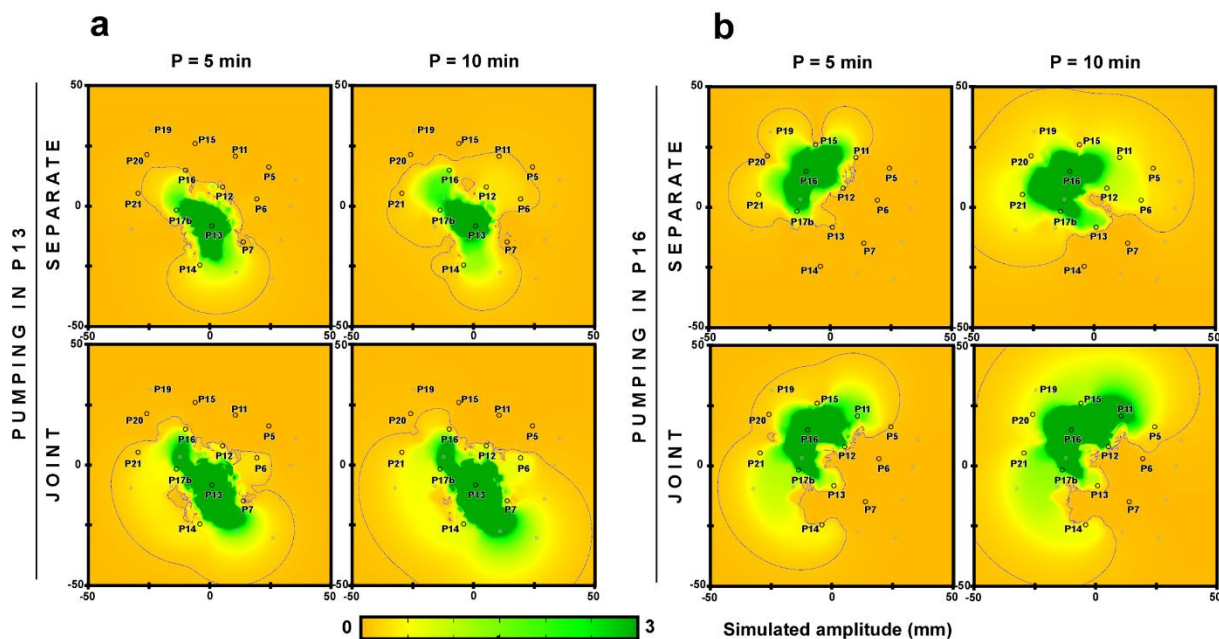
This section discusses the maps of the amplitude and phase-offset spatial responses (Figure 8) simulated with the property maps obtained from the separate inversions and presented in the previous section (Figure 5). These maps present the propagation of the oscillatory signal in the field. The amplitude of the oscillation is presented with a green color showing the highest amplitude responses (near to the pumping point) and an orange color in the area of the site where the signal has lowered ( $< 1\text{mm}$ ) or totally attenuated. The phase of the oscillation is indicated with a low offset (in blue), near the pumping point, and with high offsets (in red). Notice that the offset is cyclic, meaning that the signal response can be in phase with the pumping point even at a long distance from it, but with one (or more) oscillation cycle delay. However this is purely theoretical, as at such distances the signal has generally a too low amplitude to be measured.

A clear evolution is visible in the interpreted simulations of the responses to an increasing period of signal. The impacted area tends to increase with the period of oscillation, although the amplitude of pumped flow rate remains the same. In fact, for a period of oscillation of 10 min, low amplitude responses appear in areas around the pumping locations that were not impacted with a period of oscillation of 5 min.



**Figure 8:** Maps of **a** amplitude and **b** phase offset responses simulated over the study site with the inverted property distributions. These maps are presented for the two pumping wells and for the two periods of pumping signal ( $P = 5, 10$  min.). The grey isolines in the amplitude maps represent the limit to amplitudes  $< 0.1$  mm.

A comparison between the simulations of the measured responses obtained for each separate inversion and the joint inversion is presented in Figure 9. The comparison focuses on the amplitude responses, which are easier to visualize than the phase-offset responses.



**Figure 9:** Comparison of the maps of amplitude responses simulated over the study site with the property distributions from the separate inversions ( $P = 5, 10$  min.) and from the joint inversion. These maps are presented for the two pumping wells (**a** P13, **b** P16) and for the two periods of pumping signal ( $P = 5, 10$  min.). The grey isolines in the amplitude maps represent the limit to amplitudes < 0.1 mm.

In the simulations made with the result of the joint inversion, when increasing the period of oscillation, an increase of the area impacted by the generated oscillatory signal is visible; this was observed previously in the simulations made with the results of the separate inversions.

By comparing the simulations made from the joint and separate models, it appears that, in the joint simulations, the areas associated to the higher amplitudes are close to the ones obtained in the  $P=5$  min separate simulations. However the areas associated to low amplitude responses are more extended in the joint simulations, closer to the simulations obtained with the  $P=10$  min models. These observations would tend to indicate that the lower period would rather mobilize flows associated to close conductive areas, while higher periods would mobilize flows in more extended areas, generating more low amplitude responses.

## 5. Discussion

The use of oscillatory data to characterize the spatial hydraulic properties of the study site permitted successful creation of an image of the high heterogeneity existing at this scale in the aquifer. Furthermore, using oscillatory data here provided three main advantages. Firstly, oscillatory data present advantages compared to pumping responses analyzed in a temporal domain, as the oscillatory responses can be simulated in a model in the frequency domain, leading to quick computation time, equivalent to simulations in a steady state, while also characterizing both  $T$  and  $S$ . Furthermore, compared to pumping tests aiming to reach a steady state, the global pumping duration can generally be reduced as, in this case, 6-7 generated oscillations are sufficient to extract exploitable responses. Secondly, the oscillatory responses could be easily extracted from the field natural signal which is highly influenced by the tidal signal of the nearby river (through a FFT). This was less the case for drawdown curves of constant pumping rates led on the same site, for which the extraction of the responses became problematic (in particular, separating the tide signal is not as easy as extracting pure oscillation signals without long-term measurements). Thirdly, oscillatory pressure signals propagate in water, and their spatial responses are extractable, even with low amplitudes (mm amplitudes at a field scale in this study). This property was useful in this study case as, due to the high heterogeneity of the field site, some pumping wells on the site show a quick growth of their drawdown when increasing the pumping rate, which can sometimes lead to an emptying of the well. Thus, in such pumping wells, oscillatory pumping allowed for a spatial characterization with low pumping rates (also beneficial in this case as the study site is contaminated). Moreover, with oscillatory signals, various distances impacted by the pumping can be explored without having to increase the pumping rate. In fact, as shown in these results, the area impacted by the pumping can be extended by increasing the period of the oscillatory signal.

Similar behavior was observed by Cardiff et al. (2013) in their tomography on a synthetic heterogeneous case at a decametric scale, with periods of oscillations of 5 s to 5 min. They concluded that higher frequencies could provide better information on the properties around the wells, while lower frequencies provided more information on areas beyond the well locations. Therefore they suggested performing joint inversions to combine the information carried by both higher and lower frequencies. When applying oscillatory signals in a karstic aquifer, Fischer et al (2018) noticed that with lower periods of oscillatory signals, the responses seemed to hold more specific information about the most conductive paths in the aquifer (karstic conduits), while with higher periods the responses were affected also by flows in less conductive paths (fractures and fissures in the rock). Similar behavior was already suggested by Rabinovich et al. (2015), who used a simple model to show that higher frequencies would generate flows more specifically in the most conductive areas of an aquifer. This could also explain why the conductivity distributed model interpreted from constant-rate pumping tests led on the same site as that used by De Clercq et al. (2020) is closer to this study's transmissivity map inverted with the highest period (10 min) measurements (a constant signal being comparable to a signal with an infinitely high period).

The results of hydraulic imaging from this study, obtained from responses to oscillatory signals at different periods, tend to validate these observations. When performing a joint inversion, as described by Cardiff et al. (2013), the result appears better constrained, suggesting that the information from the different periods is non redundant. In this application in an alluvial aquifer, the main difference in the information held by the responses to different periods of oscillations appears to be the area of groundwater impacted by the oscillatory signal. Therefore, with lower periods, the oscillatory signal impacted mostly conductive zones near the pumping wells, and with higher periods, the signal also generated low responses around the pumping wells, in less conductive areas. In a recent application comparing the results obtained on the

same site with oscillatory data and constant-rate data, Cardiff et al. (2019) observed that the characterization with oscillatory data provided lower conductivity values in the zone associated to low conductivities, thus accentuating the contrast between high and low conductivity distribution. This could be explained by the fact that low-period oscillations generate responses with spatial distributions highly dependent on the contrast existing in the property distribution around the pumping well.

In this application, the oscillatory responses were extracted from a background tide signal. An eventual impact of the tide signal on the groundwater condition (groundwater level) during the pumping has been considered as negligible. This is mainly due to the fact that the background tide signal, throughout the pumping tests, generated a movement of the water table not exceeding 10 cm ( $< 2\%$  of the water column). Nevertheless, it is known that during the most influential sea tide ranges at this field site, the groundwater level can naturally move up to 1 m, which then might have an impact on the groundwater condition. Therefore, before performing a pumping investigation, it has been important to firstly study the movements induced by the natural tide signal on the groundwater level of this field site, without any other solicitation. It can also be noticed that the sea tidal signal (comparable to an oscillation) itself could be considered as a signal for the field characterization, thus also totally avoiding the need to pump in the aquifer. However, its important period (about 12 h) would be rather more interesting for characterization of sites of larger areas, for example a site at a kilometric scale, as presented in Jardani et al. (2012). It was also hypothesized that the main flows were horizontal in this alluvial aquifer and Darcy's law was employed to simulate these flows. The authors believe that this assumption is correct for a major part of the field site. However, locally at the pumping boreholes, some vertical flows might occur. In particular, a participation of the underlying chalk aquifer is possible at the pumping locations, explaining why the amplitude responses are more distinct at the pumping locations than at the other wells of the field site.

## 6. Summary and conclusion

Natural or induced oscillatory signals in hydraulic tomography have been a topic of interest for field characterization in hydrogeology for several years. Theoretical developments and field applications have shown the advantages brought by these signals.

The results of the characterization described here, led with responses to oscillatory pumping signals in a complex alluvial aquifer, allowed for an imaging of the heterogeneity of the subsurface properties at the decametric scale. Responses to two different periods of oscillations (5 and 10 min) were used. The results show that increasing the period of oscillation results in an increase of the area impacted by the oscillatory signal induced by the pumping test. The lowest period of signals (5 min) provided more information on the conductive areas close to the pumping wells, while the highest (10 min) permitted better characterization of the less-conductive areas around the pumping location, with the low amplitude responses. Performing a joint inversion with all data obtained with the two periods of oscillations results in less-uncertain property maps than the ones obtained with separate inversions, thus confirming the fact that both datasets carry different and complementary information.

Oscillatory signals provided, for this application, several advantages. Firstly, spatial responses are exploitable only after several oscillations (6-7 in this case), thereby allowing for a reduction in the pumping time. Then, the ability to solve the model in a frequency domain with the oscillatory responses, rather than in a time domain, permits a considerable reduction in the computation time required for the inversion. Secondly, the data processing allows extraction of the responses even in an environment with a strong natural forcing, like in this case the tidal variation induced by the nearby Seine River. Finally, the pumping rates can be globally lowered as, for example in this case, an oscillation's amplitude of an order of magnitude of millimeter

560 can be extracted from measured responses with global decimetric variations through a FFT  
561 process.

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